VOLUME XLVIII NUMBER 2

THE

JOURNAL OF GEOLOGY

February-March 1940

A TENTATIVE CLASSIFICATION OF SAND DUNES ITS APPLICATION TO DUNE HISTORY IN THE SOUTHERN HIGH PLAINS

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ABSTRACT

PART I. Existing sand dunes fall naturally into two groups—*complex* and *simple*, the former being much the more common. Variable factors, such as wind direction, depth of sand, irregularity of vegetal growth, etc., are responsible for the rarity of the simple dunes. It is only by first studying simple forms, however, that one can discern the origin and history of surfaces of complex form. Following is a basic classification of simple dunes which is at the same time genetic and naturalistic. It is based on the assumption that the sand-moving wind blows with unvarying direction.

Simple Dunes

A. Bare Surfaces or Loose Sand
   I. The barcan dune. An isolated bare-sand hill on a nonsandy base
   II. The transverse dune series. Formed on bare, loose sand of "unlimited" surface area and "unlimited" depth
   III. The isolated transverse dune ridge. Formed (frequently with human aid) from bare, loose sand of unlimited surface area, but shallow depth
   IV. Lee dunes
      1. Wind-shadow dunes ("umbracer" dunes). Longitudinal dunes. Formed from a continuing (unlimited) sand supply in the lee of a bedrock obstacle
      2. Shrub-coppice dunes (see p. 124)
      3. Source-bordering lee dunes ("umbrafon" dunes, lee-source dunes). Formed from a continuing (unlimited) sand supply leeward from a source of sand of limited area (e.g., stream flood plain)

B. Formed by Wind in Conflict with Vegetation
   I. Shrub-coppice dune cluster. Formed in and to leeward from bunch or clump vegetation, such as mesquite bush, on an unlimited and smooth surface of very shallow sand

II. (*a*) Blowout or parabolic dunes; (*b*) elongate-blowout dunes; and (*c*) windrift dunes. Formed by gentle, moderate, and strong winds, respectively, on deep sand with shrub- or grass-covered surface

Under the heading "Complex Dune Forms" is considered the ideal simple case of two equally effective sand-moving winds blowing at right angles. It is pointed out that even this degree of complexity is much simpler than that of many of the well-known sand-dune areas.

PART II. A study of dunes in the southern High Plains by means of vertical aerial photographs reveals:

1. Up to the decade from 1920 to 1930, active sand dunes were insignificant in number and total area, compared to the anchored dunes of Recent or post-Pleistocene age.

2. There has been a systematic shift in the direction of the prevailing sand-moving wind during the last 15,000 years (estimate), such that winds which formerly blew toward S. 70° E. have been replaced gradually by modern winds blowing N. 20° E. in most of the region. For convenience in description these dunes are divided into three series: I, II, and III, from youngest to oldest.

3. An unusual series of large parallel windrift dunes, indicating strong persistent winds, was formed around 15,000 years ago. Sand dunes of this type (Series III) are apparently not forming at present to any noteworthy degree, either in the interior of North America or along the coasts.

INTRODUCTION

The study of dunes in the southern High Plains was started in 1928, when the first aerial photographs of a portion of this region, made by the Fairchild Aerial Surveys, revealed a type of dune (the windrift) never previously described in the interior of the United States. They furthermore revealed the effects of prevailing winds which do not blow in that region today. These early photographs showed that, in broad plains, dunes are sensitive and reliable indicators of the direction and strength of the prevailing winds of the past.

The study was continued in 1936 and 1937 with the help of the Section of Climatic and Physiographic Research of the Soil Conservation Service. Aerial photographic maps of other portions of the High Plains were at that time being rapidly completed. Their study and use in field work corroborated the earlier conclusions and yielded additional information about various factors contributing to wind effectiveness—factors such as the nature of the vegetal cover of the sand surface and changes in ground-water level.

This paper is divided into two parts. Part I is a system of classification of dunes and comprises the bulk of the study. Part II is a historical paleoclimatic study in which aerial maps are extensively used. The conclusions of Part II could not have been drawn without the aid of carefully assembled maps showing the directions of former prevailing winds as revealed by the alinement and form of dunes long

since anchored. Neither part of the paper attempts quantitative studies, important as they are.

The classification of Part I is but tentative and must stand the tests of prediction and use. It will undoubtedly be modified as more detailed studies are made. Fundamental to the classification is the proposition that knowledge of *dune form* is both a necessary and a sufficient prerequisite to any classification of a dynamic nature.

The system of classification here advanced is also simpler than nature, since the attention is focused upon outstanding and easily described features which, nevertheless, grade into one another, through intermediate forms not so easily described. If the immense complexity of dune forms is to be understood, the classification must be simplified by arrangement in groups which are as natural as possible, but which are admittedly gradational.

The concept of "the most effective sand-moving wind" is fundamental. Wind may blow from various directions and still not move an appreciable amount of sand or reconstruct dune topography greatly. Terms such as "wind direction" and "wind velocity" refer, consequently, to *effective* wind direction and velocity.

This study does not involve a complete analysis of dune forms. Slight attention is paid to those features formed by wind which is scouring much more rapidly than it deposits. The treatment in Part I is, however, sufficiently inclusive for the purposes of Part II.

PART I. A TENTATIVE CLASSIFICATION OF SAND DUNES

Simple Dune Forms[1]

A. BARE SURFACES OF LOOSE SAND

1. THE ISOLATED BARE-SAND HILL ON NONSANDY BASE (THE BARCAN DUNE)

The barcan dune is a crescent-shaped hill of bare sand, which moves slowly across a relatively flat nonsandy surface. The "horns" of the crescent move in advance of the main mass of sand and are always pointed with the wind. The windward or "weather" side is a gentle slope; the lee side is a steep "sandfall" which usually has the angle of repose of moist sand (Figs. 1, 2, and 3).

When a dry wind is blowing, sand is scoured from the weather

[1] The most effective sand-moving wind blows with constant direction.

side, rolled or carried to the summit, and there blown free from the surface. The coarser sand grains drop at once down the sandfall; the small grains, however, continue their flight downwind to varying distances depending upon the velocity of the summit wind and the violence of the eddies in the lee of the dune. This stream of flying sand at the summit makes a dune appear to have a "smoking" crest.

Barcan dunes arise from previously existing hills or mounds of bare, loose sand. Since such hills may arise from several other types of dunes, a discussion of their origin must be postponed until later in the paper. It is only the behavior of the isolated sand hill under wind attack that is to be considered at this place.

Where such sand hills appear under conditions of constant wind direction, the barcan form may develop in a few weeks, days, or hours, depending upon average velocity and continued dryness of the sand surface. One isolated barcan constantly and gradually diminishes in size as it travels, provided, of course, that the base is entirely nonsandy. In a barcan series, however, the larger dunes become even larger at the expense of the smaller. The smaller, moving faster, overtake the larger and then merge with them.[2] The "smoking crest" is the site of winnowing, where smaller grains are removed from the dune and blown entirely away. In such a dune it follows that the average size of sand grains should increase as the size of the dune decreases.

Barcan form is, of course, chiefly a function of wind direction, though possibly also of wind velocity. Under the simplifying assumption of constant direction, however, form would probably depend upon velocity much as shown in Figures 4, 5, and 6. It is not possible to cite definite proof of this graphically shown relationship between form and velocity other than the experimental proof that wind eddies persist farther to leeward under strong than under gentle winds. It will be shown that such eddies are very effective in localizing sand deposition behind a sand hill undergoing erosion.

In actual cases the wind direction is never exactly constant. The effects of constant direction are thus a matter for speculation, except in so far as existing cases approximate the ideal straight wind. This

[2] This may be confirmed by noting that in an area of barcans of different size the small dunes are found more frequently directly behind large dunes than in front of them.

they undoubtedly do to such an extent that the degree of extrapolation from the known to the unknown is entirely within the bounds of reason. It will be seen later that this objection loses its force in the case of most of the other dune forms considered. The effects of variable wind direction are considered under "Complex Dunes."

The sharp dune crest is the cause of eddying, perhaps also the result of it. It may in fact be futile to speak of the sharp crest as being either the cause or the result; both seem to be linked together inseparably. C. J. Whitfield has shown that artificial grading of the sharp crest of a barcan dune, in the southern High Plains near Dalhart, Texas, so destroys the eddying to leeward that the dune no longer migrates as formerly. On the contrary, "once a dune [crest] is broken down [*sic*] huge quantities of sand are carried beyond to another area and there spread over the sub-stratum. . . . . As a result of the application of these methods dunes were lowered as much as 15 feet in a five-month period."[3]

II. UNLIMITED SURFACE AREA AND UNLIMITED DEPTH OF BARE, LOOSE SAND[4]

Area and depth may be considered "unlimited" if they are large in relation to the length and height of the dunes which have formed previous to the time that the examination is made. In the case of any winds now blowing in the continental interior of the United States, an area measured in tens of square miles and depth measured in hundreds of feet would both be called "unlimited" within the meaning of this paper.[5]

1. *Gentle wind.*[6]—A "gentle" wind blowing with constant direction across a bare sand surface of unlimited area and depth will pro-

[3] "Sand Dunes in the Great Plains," *Soil Conservation* (March, 1937), pp. 208–9.

[4] Unvarying wind direction is assumed.

[5] The length of time during which a constant wind is permitted to move sand on a given surface will to a certain extent determine the area and depth which are to be considered "unlimited." This is true because, up to certain unknown limits, the longer a constant wind blows, the larger will be the resulting dunes. Thus the sand base, which was well covered in the early stages of dune growth, may be uncovered at a later time.

[6] Using as a guide the average of measurements of velocity 100 feet above ground, taken hourly over a period of many years in the High Plains, those velocities less than 10 miles per hour will be tentatively designated as a "gentle" wind. Winds averaging 10–14 and those more than 14 miles per hour will be designated "moderate" and "strong," respectively (Charles P. Loomis, "The Human Ecology of the Great Plains Area," *Okla. Acad. Sci. Proc. 1936*, pp. 14–28; esp. fig. on p. 16).

duce an evenly spaced series of long, parallel sand ridges extending straight across the wind direction. These parallel ridges, under ideal conditions, are nearly identical in shape. The windward or "weather" side is a gentle slope subject to wind scour as the wind moves upward toward the crest. The lee side is subject to sand deposition as grains fall below the crest and slide down a steep surface, the "sandfall," at the angle of repose of loose sand. Such an array of dunes is a *transverse dune series* (Fig. 7).

Eddies form to the lee of the crest, just as in the barcan dunes previously described, and the moving sand is "winnowed" at the zone of maximum turbulence, the finer grains drifting away, the coarser falling down the lee side.

More observations need to be made on the transverse dune series, where exact measurements of wind velocity are available. Preliminary observations, however, seem to show that size (height and "wave length") is more or less independent of the average velocity, up to a certain figure, but is dependent upon depth of sand, area of surface, and length of time during which the series has been growing.

Where wind direction is variable, the causal relationship between size of dunes and other factors is too complicated to permit either a clear or a simple statement to be made.

2. "*Moderate and strong*" *winds*.[7]—The transverse dune series should form under moderate and strong winds of constant direction at a more rapid rate than under gentle winds and possibly should attain greater ultimate size. Given unlimited depth and area of sand, the relationship which holds between velocity, time, and resulting size (height and "wave length") of the transverse series is, however, almost entirely a matter of speculation. There is a great gap in the array of facts which are pertinent to the determination of this relationship in the natural state—apart from artificial experiments on sand ripples.

III. UNLIMITED AREA, BUT LIMITED, OR SHALLOW, DEPTH OF SAND[8]

1. *With human aid in freeing the sand surface from all vegetal cover, i.e., the plowing of large tracts of sandy soil.*—With wind of constant

[7] Average hourly velocity 100 feet above ground is 10–14 and more than 14 miles per hour, respectively.

[8] Area is measured in square miles, but depth is measured in feet, say, less than 5 feet.

direction the sudden appearance of a broad surface of loose, shallow sand will cause the formation of *isolated transverse dune ridges* (Fig. 8) extending straight across the wind direction. These sand ridges are not a regular series of dunes but are unevenly spaced, the nonsandy base being exposed between them. Small ridges migrate faster than large ones if the environmental conditions are the same.

They do not endure long even under the most constant conditions. With slight irregularities in wind direction, or in the resistance of the sandy soil, they go to pieces in a few days or weeks, yielding isolated sand hills of the "barcan" type.

Emmanuel de Martonne has suggested that these isolated transverse sand ridges are caused by the coalescing of a group of barcans. "Groups of barcans standing side by side and close together become long ranges of sand hills at right angles to the prevailing wind. Vast regions of such sand hills are formed by the multiplication of chains of barcans."[9] While this undoubtedly takes place at certain times and places, it is the opinion of the writer that the reverse process is much more common. That is, the isolated transverse dune ridges frequently are formed without going through the barcan stage at all; though once formed, provided the sand is uniformly shallow, they may be expected normally to result in an array of barcan dunes.

Under the ideal conditions here assumed, of constant wind direction and uniformly shallow loose sand, it seems evident that the only important effect of variable wind velocity would be on speed of travel and not on size of dune ridges.

Such isolated transverse ridges are not to be confused with lee dunes. The latter (see p. 120) are the result of sand accumulation on the lee side of an obstacle or of a local sand supply.

2. *Without human interference in the liberation of a sand surface from the restraining influence of vegetal cover.*—Under natural conditions it is difficult to conceive how a broad surface of loose sand could be liberated with sufficient abruptness to permit the isolated transverse dune ridge to form. Instead, under natural conditions, small areas, a few feet or a few yards across, are freed from restraint separately from their surroundings, thus yielding the isolated "blowout dunes" to be described later.

[9] *Shorter Physical Geography* (New York: A. A. Knopf, 1927), p. 233.

IV. LIMITED AREA, BUT UNLIMITED DEPTH OF SAND

The case of a very deep deposit of loose sand, which at the same time has only a slight surface area (ignoring for the moment the influence of surface vegetation), hardly occurs in nature and therefore need not be considered. The concept of "limited area but unlimited depth" serves, however, as a natural introduction to the common case of a limited area but a continuing sand supply (which may be said to be unlimited in depth within the meaning of this paper, even though the depth of sand is shallow). Examples of shallow though continually replenished sand bodies are: (1) stream flood plains; (2) the margin of a plateau surfaced by a thick but poorly consolidated sandstone yielding abundant loose sand on weathering at the plateau margin; and (3) an ocean or lake beach.

1. *Lee dunes: dunes formed under constant wind direction in the lee of an obstacle or of a source of loose sand.*[10]—

a) Wind-shadow dunes ("umbracer" dunes).—In an area of sand supply or sand movement—where the loose grains, though perhaps forming only a shallow layer, are constantly being replenished by weathering or abrasion—eddies behind obstacles of any nature will be the site of sand deposition. The continued existence of *wind-shadow dunes* will depend upon the type of obstacle.[11]

(1) Wind-shadow dunes behind permanent bedrock obstacles, in an area of sand supply or sand movement. Where the obstacle is an isolated bedrock hill and the wind direction is essentially unvarying, sand is deposited downwind from the hill in an elongate ridge. The shape of this ridge is variable depending upon height of the hill, velocity of wind, and quantity of available sand. Where the hill is not too high, but the sand is plentiful and the wind is strong, such dunes are quite long and narrow, tapering to a point in the down-

[10] Limited bare-sand area and a continuing sand supply, which is considered to be of "unlimited" depth within the meaning of this paper.

[11] Though a detailed analysis of the aerodynamics of sand deposition in eddies would not be suitable in this paper, it should be pointed out that most eddies have an axis which may be horizontal, vertical, or inclined and which may lie in almost any conceivable position with respect to the wind direction. Some eddies are pointlike, in which case the turbulence is probably more complicated and may be more effective in dissipating the wind's energy and inducing sand deposition than in the case of the tube-shaped eddy behind a long transverse obstacle.

wind direction. They are called *longitudinal dunes* (Fig. 9). The first description of dunes of this type was published by the Geologic Survey of India.[12]

Longitudinal dunes of remarkable perfection have recently been revealed by aerial photographs at the western edge of the Moencopi Plateau in northeastern Arizona (Fig. 10). In this case the plateau summit and the cliff face are supported by soft, thick sandstones (Navajo sandstone and perhaps others). The prevailing southwesterly wind sweeps upward through the canyon heads and northeastward across the plateau summit, picking up loose sand and scouring additional grains as it moves. The sand is deposited in dune form where the eddies occur, that is, above and behind the promontories which lie between headward-eroding canyons of the cliff face. Some of these dunes are nearly 2 miles in length, 50–100 feet in width, and 10–20 feet in height. Once formed, they do not migrate as a unit (so long as the wind maintains the same direction), though there is hardly any definite limit to the length to which they may grow if conditions remain sufficiently constant. There are suggestions that some of the Moencopi longitudinal dunes in the recent past were perhaps 3–5 miles in length.

Unvarying wind direction is, of course, essential to the formation of longitudinal dunes of the Moencopi type. Variations of a degree or two in prevailing wind direction, if continued for only short periods, would trim the dune extremities and shorten them very rapidly. In such a case the extremity of each longitudinal dune would become the point of origin of a train of barcan dunes migrating downwind (see section on "Complex Dunes," p. 130).

If sand is very easily available for wind transport, a narrow series of transverse dunes may arise on top of the longitudinal dune. Where the sand must be blown out of a local depression, it is usually so retarded that it does not form the longitudinal dune at all but merely a "blowout dune" (see p. 126).

There are plentiful suggestions that longitudinal dunes may form on flat surfaces without the aid of obstacles in arresting the flying sand. On the summit of the Moencopi Plateau are straight ridges of

[12] W. T. Blandford and H. B. Medlicott, *Geology of India* (2d ed.; Calcutta, 1893), pp. 455 ff.

sand 1 or 2 miles in length several miles distant from the canyoned edge of the plateau. These straight parallel ridges are rather closely spaced and give no indication that a bedrock obstacle was the cause of their existence. It is not a certainty, however, that the ridges are not part of a great system of "windrift dunes" (to be described later) each consisting of a wind-scoured trench between two parallel ridges of loose sand. Cornish, describing the longitudinal dunes of the Rann of Cutch, says:

> The longitudinal dunes are largest and widest apart where the wind blows most strongly, and get nearer together as we proceed from south and west to north and east. Then a district is reached where the longitudinal ridges are laid down so closely that they are frequently united in a transverse ridge; and, finally, the longitudinal striping is reduced [*sic*] . . . . to a subordinate feature of the windward slope of transverse dunes. Thus the longitudinal striping is in direct relation with the force of the wind and with the burden of sand which it bears. I am not aware that there is any evidence to show that there is, or has been, a similar distribution of extraneous obstacles.[13]

On the other hand, the observations of the writer indicate that longitudinal dunes are unquestionably formed downwind from some type of obstacle, though it may not be more than an older and more wind-resistant pile of sand.

(*2*) Wind-shadow dunes formed behind clumps of bush, of a type which does not migrate readily, are worthy of mention because of the significant size which they sometimes attain and also because they may be the source of a train of barcans which detach themselves from the parent "wind-shadow dune" and migrate to leeward.

The most common type of wind-shadow dune behind a clump of bush is one in which the bush migrates with the sand. This type, called "shrub-coppice dunes," will be considered under the heading "Wind in Conflict with Vegetation."

b) Source-bordering lee dunes ("lee-source" or "umbrafon" dunes).—A source bordering lee dune is the type of dune ridge which develops on the lee side of an area of loose sand, for example, on the lee side of a stream flood plain or landward from a sandy beach. The wind may be either gentle or strong and need not be of unvarying direction as in the case of other simple dune forms considered in the

[13] V. Cornish, "On the Formation of Sand Dunes," *Geog. Jour.*, Vol. IX (1897), pp. 292–93.

foregoing paragraphs. The constantly replenished sand supply is of "unlimited depth" within the meaning of this paper.

The height of these dunes will depend upon the constancy in position of the source and upon the degree of exposure of the dune summit. On riverbanks such dunes do not usually grow to great height or width, because of the variable position of sandy river beds. They are, however, frequently found to be of great length. A source-bordering lee dune approximately 12 miles long is found on the north side of the Canadian River near Canadian, Texas. Another is found near Waynoka in Woods County, Oklahoma.

Because of the tendency of rivers to change their channels in a series of "steps" or sudden "jumps," source-bordering dunes are commonly found in parallel series. Behind sandy beaches, on the other hand, these dune ridges may grow to great size because of the relatively constant position of the source of sand, constant wind direction, etc.

Source-bordering lee dunes seldom are regular sinuous ridges of uniform height and width (Figs. 11, 12, and 13). They may originate as an interlocked chain of elongated petal-shaped plates of sand with a spoonlike depression in the middle of each (see "Blowout Dunes," p. 126). Likewise, once formed, they may be eroded by the development of such spoon-shaped blowouts.

Dunes of this type on the south shore of Lake Michigan have been called "foredunes."[14] The author believes, however, that this name emphasizes subsequent life-history of these dunes rather than the origin of the elongated dune ridge itself.

V. LIMITED AREA AND SHALLOW DEPTH

Small tracts of bare sand, not more than a small fraction of a square mile in area or more than a foot or so in depth, are usually caused by the destruction of a former plant cover. Such small bare-sand areas are very common in grassland or desert regions and will be discussed under "Wind in Conflict with Vegetation" (p. 124). In situations where vegetation is not the controlling factor, the behavior of such sandy surfaces is not sufficiently different from cases already considered under "Unlimited Area and Shallow Depth" and

[14] G. B. Cressey, "The Indiana Sand Dunes and Shorelines of the Lake Michigan Basin," *Geog. Soc. Chi. Bull. 8* (1928), pp. 38–39.

"Limited Area, but Unlimited Depth" to warrant close attention at this place. It is sufficient to point out that, under gentle and moderate winds of constant direction, scour of a small bare surface of shallow sand results in the excavation of a basin and the deposition of a definite type of "lee" dune fitting closely around the lee margin—the "blowout dune" discussed later. With strong winds, if the sand is very shallow, the result may be no dune at all but merely a thin veneer of the coarsest sand fractions in process of movement as individual grains, without any organization into recognizable dune form. Where the sand is of sufficient depth, however, there will arise a longitudinal dune.

B. WIND IN CONFLICT WITH VEGETATION[15]

I. VERY SHALLOW SAND WITH SMOOTH SURFACE[16]

For example: A dry-stream flood plain in an arid region, or a sand-surfaced alluvial fan.

1. *Wind in conflict with bunch or clump vegetation, such as mesquite or oak bush (shinnery), in the absence of other effective sand binders such as the grasses and Russian thistle: the "shrub-coppice dune."*—On the disappearance of the grasses and other effective sand binders with climatic change, overgrazing, etc., remaining clumps of shrubbery may trap a noticeable amount of the blowing sand. Mesquite bush, in the southern High Plains for example, grows vigorously on loose sand and is not readily killed by slow sand burial. Sand which falls within the bush may thus stay for a considerable time. If this process continues, a mound of sand eventually is built and held together by the coppice. The windward side of such a protected sand mound or coppice dune is scoured and eroded at the same time that sand accumulates within the bush and on the lee side. In time, this erosion on the windward side exposes the roots and kills the plant. The sand which is deposited on the lee side, however, furnishes suitable soil for the advancing bush. In this manner the dune migrates with the wind, leaving a trail of dead mesquite wood. The lee side possesses the smoother but not necessarily the steeper slope. In fact, the scoured windward side is frequently vertical because of the an-

[15] Constant direction of one effective wind is assumed.

[16] A few inches to 1 or 2 feet in thickness.

choring effect of the roots and buried stocks of bushes. These dunes migrate very slowly, an average rate being perhaps 1 or 2 feet a year (Figs. 14 and 15).

Shrub-coppice dunes supported by mesquite bush are present in vast numbers in southeastern New Mexico and in adjoining districts in the southern High Plains. In the High Plains the maximum height is approximately 10 feet, and the maximum diameter is near 50 feet. Though the largest of these dunes are found where the sand is deepest, other factors, such as local concentrations of wind force or differences in dune age, have no doubt had their effect on the size of shrub-coppice dunes.

In the southern High Plains clumps of yucca and "shinnery" oak bush give rise to coppice dunes in many places; those on yucca, however, are usually too small to be classified with dunes, and those on the shinnery are very broad and flat.

R. D. Reed[17] has suggested that, in the San Joaquin and Salinas valleys of California, the scouring of sand from one side of this type of dune more than the other is due to the greater dryness and resulting large area of exposed bare soil on the south slopes as compared to the more densely vegetated north slopes. This, in his opinion, makes it possible for south winds to do more work than the north winds. Such a process may be in operation there and elsewhere, but it is doubtful whether it is the controlling factor in the migration of coppice dunes in the Great Plains. In southeastern New Mexico these dunes migrate toward the northeast. The dying mesquite shrubs on the southwestern side and the vigorously growing coppice on the northeastern side are a *result* rather than a *cause* of wind scour on the southwestern sides of these dunes. The correct explanation of such dune motion in the southern High Plains thus seems to lie in the relative effectiveness of dry persistent winds as contrasted with moist and less frequent winds from the north, northwest, and northeast.

A typical shrub-coppice dune series, barring a reversal of the climatic trend, is the precursor of greater sand concentrations to come; it is the first topographic manifestation of increasing aridity on a smooth surface of shallow sand, which was previously anchored by grasses and associ-

[17] "Effect of the Wind in San Joaquin and Salinas Valleys" (abst.), *Bull. Geol. Soc. Amer.*, Vol. XXXVII (1926), pp. 214–15.

ated vegetation. Such dunes probably cannot endure in active migration for many decades, because the principle that small dunes migrate faster than large ones (if it applies in this case) should concentrate the sand in ever larger and more sparsely distributed sand elevations. These should ultimately change to the isolated transverse dune ridge, or, after the complete elimination of the shrub coppice, to the barcan type of topography.

2. *Wind in conflict with grass-covered smooth surfaces on very shallow sand.*—Dunes do not originate on grass-covered surfaces unless the grass is locally killed and the surface is thus freed from its restraining influence.

II. DEEP SAND WITH SHRUB COVER

If one could observe the effect of increasing aridity on a smooth grass-covered surface underlain by deep sand, he would no doubt find that gradual replacement of the grasses by drought-resisting shrubs would facilitate the development of shrub-coppice dunes. In nature, however, such deep sand seldom has a smooth surface; on the contrary, it is usually scarred by a series of old dunes formed during an earlier cycle of wind activity and later anchored by vegetation. The roughness of these surfaces effectively prevents the formation of a large series or cluster of the shrub-coppice dunes. Though occasional isolated small groups of coppice dunes develop on deep sand, the common forms are the much larger "blowout dunes" discussed in the following.

1. *Gentle wind of constant direction;*[18] *the "blowout" or "parabolic" dune.*—If the cover of vegetation is locally killed, say at a watering place, a trail, or a farmstead, the persistent wind may scour away the underlying sand, thus exposing and killing the root-systems of the anchoring grasses. If conditions favor the growth of vegetation, it may once more cover the excavation rapidly enough to prevent further wind damage. In fact, if the environmental conditions are sufficiently favorable, grasses may undergo a large degree of damage by natural processes without permitting the wind to scour the soil away from the roots. On the other hand, if the climate is becoming progressively more arid, or if the ground-water surface is being

[18] See p. 117.

lowered by other means, the vegetative cover may find itself unable to grow as rapidly as its roots are being uncovered. In this case the wind will continue to remove sand from the damaged spot until conditions other than the growth of vegetation stop the erosion.

A continuation of this process will leave a recognizable basin in the sand surface. Since the coarser sand fractions usually do not travel far, some of this sand will accumulate near the margin of the excavation on the leeward side, thus forming the crescent-shaped sand ridge and basin which are the typical form of the "blowout" dune. The excavation is usually oval in shape; the rim of sand fitting closely about the lee side is crescent-shaped, the wings of the crescent opening toward the winds[19] (Figs. 16, 17, and 18).

a) Limitations of size.—The size of the area which will develop into a blowout dune may depend upon the depth to the water table or to a resistant stratum, such as a clay layer, a gravel layer, or a caliche bed. On the other hand, if the wind is not very effective, the size of the area of bare sand which is freed from its anchoring vegetation may depend upon the work of some extraneous agency, such as herds. The size of the area thus freed may in turn determine the depth to which the sand will be scoured. Regardless of causal conditions, blowout-producing winds are very insistent in pressing any advantage which they may have through damage to the vegetal cover.

Many factors may be responsible for the development of blowout dunes in restricted localities, but in the main climatic factors seem to control the time of their development. This is particularly true in the Great Plains. If one may judge from the southern High Plains, dunes of this type have reappeared and have been reanchored several times. This process appears to have been cyclic, though the interval of time between periods of dune formation was undoubtedly irregular. As will be shown in Part II, each of the main recurring periods of dune formation developed under the influence of an effective wind of different direction from that of the preceding cycle.

2. *Moderate winds,*[20] *"elongate-blowout" dunes.*—Elongate-blowout

[19] One of the best published descriptions of blowout (parabolic) dunes is the work of E. Harlé and Jacques Harlé, "Memoire sur les dunes des Gascogne," *Bull. Sec. Geog. 1919* (Paris: Imprimerie nationale, 1920).

[20] See p. 118.

dunes are very similar to the ordinary blowout dune. The wind excavates a basin and heaps up a crescent-shaped rim of sand fitting closely about the lee side. The principal difference lies (1) in the greater effectiveness of the wind in producing an elongated form and (2) in a slight migration of the basin and the sand rim in the direction of the prevailing wind (Figs. 19, 20, and 21).

The downwind migration of the elongate-blowout dune-rim, retaining all the while its crescent form, is not, as it might seem, an exception to the statement made earlier that smaller dunes migrate faster than larger ones. The leeward migration of these crescent-shaped dune ridges, the wings of which continually maintain their opening toward the wind, is not at all similar to the case of barcan dunes which migrate leeward, with the wings of the crescent preceding the higher and more central portion of the dune. Migration of the elongate-blowout is a constant struggle against growing vegetation; migration of the barcan is accomplished without any hindrance from this source. The more advanced portion of the elongate-blowout is found where the sand is deepest, because it is here that the surrounding vegetation is most rapidly and most effectively eliminated; the more advanced portions of the barcan dune are where the sand is shallowest, because this portion of the dune moves fastest.

Limitations of the size of these dunes are similar to those of ordinary blowouts, discussed earlier, except that, with the stronger wind, increased importance must be assigned to the depth of loose sand above the first resistant substratum.

a) "Nested elongate-blowout" dune series.—In at least two localities known to the writer[21] the blowout excavation has migrated *against* the wind, at the same time that a series of crescent or chevron rims of sand have been heaped up or "nested," one within another, on the lee side of the excavation. No doubt, many other examples of this type of dune series exist.

Contrary to opinions which have been advanced by others,[22] blowout and elongate-blowout dunes did not begin to form with the

[21] Not far east of Tuba City in the plateau country of northeastern Arizona; and near the Arkansas River in eastern Colorado and western Kansas.

[22] H. A. Gleason and C. A. Hart, "On the Biology of the Sand Areas of Illinois," *Ill. State Lab. Nat. Hist.*, Vol. VII (1906), p. 144.

appearance of the white man in North America or apparently with the occupancy of the continent by the American Indian. Fossil blowout dunes of all forms are by far the most numerous type of anchored dune to be found in the Great Plains at the present time. Evidence will be presented in Part II of this paper to show that certain of these dunes are probably at least 12,000 years old. There is no reason to doubt that the anchored blowout type of dune was as common throughout post-Wisconsin and interglacial time as it is today.

The "transection type of blowout" is a term that may be used to include elongate blowouts in older dune ridges (e.g., Fig. 17). The name was proposed by I. D. Scott.[23]

3. *Strong winds of constant direction;*[24] *the "windrift" dune.*—Windrift dunes differ from blowout dunes merely in the greater degree to which the activity of the wind is carried. Windrifts are longer than the elongate-blowouts described earlier. Many are a mile or more in length, though the width is only a few hundred feet. The sand rim is of a hairpin or elongated chevron shape—opening toward the wind. In the best-developed windrifts the wings are quite parallel throughout their extent. In some forms the wings diverge downwind, in which case it seems evident that the blowout was increasing in width as it moved. In the most common form, however, the wings gradually approach each other in the downwind direction, indicating that the blowout gradually became smaller as it migrated. Slight changes in prevailing wind direction may change the direction of the migrating blowout without destroying its characteristic form; if the change is considerable, however, the windrift will go to pieces and be replaced by blowouts or other types of dunes. Migration is downwind in a straight line or nearly so. The direction of migration is only slightly affected by the ordinary relief of youthful plains.

The typical feature of the windrift dune is the gap or "rift" which is frequently found at the very tip of the hairpin-shaped rim. In the last stages of blowout and sand-rim migration, when the vegetal cover is rapidly regaining the ascendancy, the final wind effect will be felt on the last remaining bare-sand surface. This will be on the

[23] "Physiography of Some Michigan Dunes" (Abst.), *Bull. Geol. Soc. Amer.*, Vol. XXXVIII (1927), pp. 140–41.

[24] See p. 118.

deepest part of the hairpin-shaped sand rim, which will usually be at the extreme end. This final spasm of activity leaves the rim with a "rift" in the downwind end. The name will be applied to the hairpin-shaped sand rims as well as to the "doublet" of parallel ridges resulting from the formation of a rift (Figs. 22 and 23). This type of dune was first described, and the term "windrift" introduced, by Belknap[25] in describing dunes in southern Greenland.

The length, breadth, and depth of windrift dunes and their associated elongated troughs depend upon factors which cannot be adequately evaluated at present. However, it is undoubtedly true that, when other conditions are equal, the breadth is a function of depth of loose sand and also of wind velocity.

Windrift dunes have been formed (1) along shores where wind has a very constant direction and a high average velocity and (2) in plains and plateaus at places where sand is deep, though apparently only at such times as are characterized by strong winds of very constant direction. They are not known in rugged mountains. *Such dunes are not forming today to any noteworthy extent in the interior of the United States, and probably nowhere in the interior of North America;* present-day winds are too variable in direction and are probably of insufficient average velocity. Their formation in post-Pleistocene time in the southern High Plains and their existence in the anchored condition until the present day will be discussed in Part II of this paper.

Complex Dune Forms

Most dune forms are much more complex than the foregoing descriptions would indicate. This is largely due to variations in effectiveness of the prevailing wind and to changes in direction. The simplest dune forms have been carefully marshaled in a systematic arrangement to make possible an understanding approach to the much more numerous complex dunes. While the immense variety of complex forms makes a thorough discussion altogether impossible, it will be profitable, nevertheless, to consider the simplest types of complexity.

[25] Ralph L. Belknap, "Some Greenland Sand Dunes," *Papers Mich. Acad. Sci. Arts and Letters*, Vol. X (1928), p. 198.

It is believed that the controlling factors are sufficiently well understood to permit the construction of a deductive or genetic system. Whenever it is possible without undue distortion of the ideas, such a construction is desirable. In the following pages therefore it will be assumed, for purposes of description only, that two equally effective winds move at right angles to each other at different times throughout the year. Though this is by no means the most common condition found in nature, it is approximated at several places in the continental interior and probably also on the coast of southern Texas. It is apparent that the above "basal assumption" is an ideally simple "complex" condition, though this does not interfere with the usefulness of the assumption for the purposes of description. Such ideal simplicity will assist the student in unraveling the mutual interplay of forces and conditions which have contributed to the great complexity of dunes.

A. BARE SURFACES OF LOOSE SAND

I. THE ISOLATED BARE-SAND HILL ON A NONSANDY BASE (THE BARCAN)

It is doubtful if the barcan form could persist under the equally effective, mutually perpendicular cross winds assumed; though if it could the speed of travel would be greatly reduced.

The effect of various combinations of wind strength on the barcan form may be inferred from the drawings in Figure 24, all of which represent forms easily found. The symmetrical barcan form of the foregoing pages cannot exist under wind attack which varies more than a few degrees.

II. UNLIMITED SURFACE AREA AND UNLIMITED DEPTH OF SAND (INTERSECTING TRANSVERSE DUNE SERIES)

The dune form resulting from two series of transverse dunes intersecting at a right angle is quite complex. Even an ideally simple case would probably be beyond the comprehension of a ground observer working without the aid of vertical aerial photographs. The chief characteristics are pointed hummocks of sand and equally numerous basins or pits. It may be described as "peak-and-fulje" topography, using a term long employed in Arabia for the enclosed basins commonly found there.

At least two intersecting series of transverse dunes are visible in

Figure 25, a vertical photograph of an area slightly greater than 3 square miles in Crane County, western Texas. The most apparent transverse series and one other are nearly perpendicular. If additional series exist in this maze of dune forms, they are oblique to the main series.

A dune surface which is best described as "intersecting transverse dune series" (apart from the fringe of barcans) is found in the Imperial Valley dunes, a few miles west of Yuma (Fig. 26). The main transverse series extends toward the northeast (toward the right); a subordinate series may extend toward the northwest. With vertical photographs one might unravel the main lines of dune movement in the Imperial Valley; with oblique photographs, however, the perspective distortion makes the task difficult. Without aerial photographs of some kind the problem is practically hopeless.

Changes in the relative strength of two mutually perpendicular effective winds produce variants of the dune pattern and also of dune size in the same manner as that discussed under "Simple Dune Forms." Cornish suggests that dune topography, which he identifies as "peak and saddle" crestlines of long transverse dune ridges (essentially the same as "peak and fulje" topography), is properly explained as follows: "The ridges had grown to a height at which the force of the wind was so much increased when drawing over the crest that the sand gave way altogether in weak spots so that furrows were produced." He further suggests that these peaks and saddles "are not necessarily the consequence of a change of wind but a form marking the attainment of a limiting size."[26] The writer's experience leads him to believe that this variant of the transverse dune series is a manifestation of two or more intersecting series and is due entirely to conflicting winds. There is no denial of the statement that dunes may attain a limiting size and develop a rounded or table-like summit. It is likewise admitted that local scour might occur, especially after unequal slight cementation through deposition of soluble substances in the interstices. The complex "peak and fulje" topography, however, seems to have no necessary connection with these ideas.

[26] *Ocean Waves* (Cambridge, Eng.: Cambridge University Press, 1934), p. 62.

III. UNLIMITED AREA, BUT SHALLOW DEPTH OF SAND[27] ELIMINATION OF ALL PLANT COVER; THE ISOLATED TRANSVERSE DUNE RIDGE

Under average conditions, with two alternately effective winds moving athwart each other at something less than a right angle, the isolated transverse dune ridge is prevented from developing; or, in case the prevailing winds of one season succeed in forming these dunes, the cross winds of the following season cause their rapid disintegration into isolated barcans. These, it will be recalled, are migrating crescentic dunes the wings of which point downwind. In this case the wings will be very short and blunt. This sequence of temporary transverse dune ridges, followed by blunt barcan dunes is the most common type of sand-dune history in that part of the southern High Plains, where recent destruction of the grass cover by man has freed a thin sandy soil for movement by the wind.

In the case of two winds of equal effectiveness moving exactly at right angles to each other, the isolated transverse dune ridge could theoretically exist, and in rare instances is actually found, though it behaves during the activity of one wind as a transverse dune ridge and during that of the other as a longitudinal dune. This condition can exist only where the two winds are very nicely balanced and very constant in their two mutually perpendicular directions. Examples are found near the shore in northern Tamaulipas, Mexico.

IV. LIMITED AREA, BUT UNLIMITED DEPTH OF SAND

1. *Wind-shadow lee dunes.*[28]—Longitudinal dunes are the most sensitive of all dunes to change of wind direction. They cannot develop the extremely elongate form of the Moencopi plateau dunes (Fig. 10), nor of those in the Rann of Cutch[29] in India, if the effective wind varies in direction more than 1° or 2°. The longitudinal dune can persist in spite of winds crossing at various angles, yet only in a blunt or rounded form. Where the cross winds are quite unequal,

[27] Area is measured in square miles, but depth is measured in feet, say, less than 5 feet.

[28] See remarks under "IV. Simple Dune Forms," p. 120.

[29] Blandford and Medlicott, *op. cit.*

the effect of the lesser wind may be to shorten the longitudinal dune by breaking it up into a train of barcans. In cross winds of equal effectiveness the longitudinal dune cannot develop to any recognizable extent.

a) The oblique longitudinal dunes.—At certain places in the United States (in southern Washington and near Canadian, Texas) one may find long, gently curved dune ridges, which on first examination appear to be curved longitudinal dunes. Their shape might indicate that they are the result of one strong wind and a weak cross wind. The writer favors the view, however, that these only simulate longitudinal dunes—that they were actually formed as windrift or elongate-blowout dunes which have been modified during their growth by a cross wind (Fig. 27). It appears that one of the paired ridges has either been blown across upon the other member of the pair or else has been partially destroyed by blowouts (see "Oblique Windrift Dunes," p. 135).

2. *Source-bordering lee dunes.*[30]—Such a dune is not much affected in shape by equal cross winds of the type postulated; it is merely slowed down in its growth. Cross winds, however, do result in special concentrations of sand at favorable localities. Examples are found on the Cimarron River in northwestern Oklahoma (Fig. 28).

V. LIMITED AREA AND SHALLOW DEPTH

The complex dunes which fall in this category are not sufficiently different from those of other classes to merit additional discussion here.

B. WIND IN CONFLICT WITH VEGETATION

I. THE SHRUB-COPPICE DUNE CLUSTER: VERY SHALLOW SAND[31] WITH SMOOTH SURFACE

Cross winds affect the shape of coppice dunes only slightly. They do, however, reduce the rate of travel but do not have any other marked effect.

II. BLOWOUTS AND WINDRIFTS: DEEP SAND WITH GRASS (AND/OR) SHRUB COVER

1. *Cross winds of equal effectiveness,* regardless of their average velocity, do not produce the simple round, oval, and elongate blow-

[30] See remarks under "Simple Dune Forms," p. 122.

[31] Few inches to 1 or 2 feet in thickness.

outs, or the trenchlike windrifts, formed under the more simple conditions described previously. The result of conflict of two equally effective cross winds is the formation of blowouts of unequal size and nondescript shape. Two-lobed blowouts are known which apparently show the effectiveness of these cross winds.

2. *The oblique windrift dune.*—If the cross winds are of noticeably different effectiveness, the elongate blowout as well as the windrift may migrate in harmony with the principal wind, though with a lack of that balanced symmetry which characterized the simple dune forms. For example, long gently curved dune ridges which seem best to be classified as "oblique windrift" dunes are found in the anchored condition north of the Canadian River, in Hemphill County, Texas. Similar oblique dune ridges, which may be modified windrifts, are well illustrated by a photograph made in south-central Washington (Fig. 27). These long parallel curved ridges extend roughly N. 70°–75° E. They are somewhat sickle-shaped, the convexity facing northwestward. The steep side of the ridges is prevailingly toward the northwest.

C. ANCHORED DUNE FORMS

The great majority of dunes in North America are now in the anchored or stabilized condition, the surface having been covered by grass, brush, or trees. It would seem on first thought that any type of dune might be found completely anchored by vegetation. Actually, however, certain forms are not known in the anchored condition, for example, the transverse dune series and barcans. Under natural conditions the readvance of vegetation, being irregular in time and place, permits blowouts to form during the process of advance on those sand surfaces not yet anchored. This destroys the forms so typical of bare-sand surfaces and leaves merely the pitted blowout surface.

By far the most common anchored dunes are the blowouts and the partially anchored shrub-coppice dunes. Windrifts are fairly common in the anchored condition around the coasts and are not rare in the continental interior. Active windrifts, however, are nearly if not quite unknown in the interior of North America and, strangely enough, are not forming along the coasts to the extent that they once did in late Pleistocene or post-Pleistocene time. An inference may

be drawn from the distribution of windrift dunes, to the effect that winds today are not so constant in direction or so strong as they were when the ice was still present in North America.

PART II. CLIMATIC CHANGES IN THE SOUTHERN HIGH PLAINS, REVEALED BY BLOWOUT AND WINDRIFT DUNES

METHOD OF STUDY

It became evident early in this study that the only safe way to proceed was carefully to assemble maps showing the direction of active sand movement as well as the direction of former movement. The form of blowouts and the position of the sand rims are better indications of present-day sand-moving winds than any available meteorological measurements of wind direction, velocity, etc. While the United States Weather Bureau Meteorological and Climatic Summaries are not sufficiently detailed to be of much assistance in analysis of probable sand movement, they are, nevertheless, not inconsistent with the results attained by observation of modern dune forms and of the direction of prevailing sand movement. The only existing accurate record of *former* wind directions in the region studied is, of course, the form of *anchored* blowout and windrift dunes.

It was soon discovered that the sequence of dune movement and wind change was similar from one locality to another. In order, however, not to run the risk of making unfounded assumptions and premature conclusions, it was decided to map the dune sequence of each locality as a separate problem in itself, until such time as the volume of assembled data would clearly point the way to the valid generalizations about the past climates of the southern High Plains. Accordingly, the following procedure was adopted:

1. At each separate locality the active and very recently active dunes were identified as Dune System I. The type of dune activity and the direction of movement (if it was easily discernible) were platted on a base map to the scale of 1:500,000.

2. At each separate locality where an easily recognized anchored dune system older that System I was found, the type of this dune activity and the direction of movement were likewise platted. These older dunes were designated Dune System II, care being taken to

see that they were actually being truncated by the active dunes of System I and that they had been formed, beyond question, under different conditions of wind direction.

3. If the older anchored dunes proved to be a mixture of more than one type of anchored dune form and of more than one prevailing wind direction, as frequently happened, Dune System III was defined at that locality, and the pertinent data platted on the base map. Where the sand deposit was deep and extensive, it was common to find three distinct dune systems represented. The two older systems were, of course, anchored forms; the youngest, System I, was in many places the active system.

4. After considerable time was spent in this type of detailed dune mapping, it became possible to correlate the relative age designations—I, II, and III—across from one locality to another not far distant, with reasonable certainty that the correlation was correct. In this way the most ancient dune forms of the southern High Plains were discovered. They should be designated as Dune System IV or perhaps V, and are located near Plains, in Yoakum County, Texas. Additional examples of the same series may exist on the Oklahoma-Texas boundary just south of the Canadian River.

Thus the relative age of the recognizable dune systems was investigated in a thoroughly inductive manner. The generalizations which are given in the following pages result from the study of these maps, in addition to other studies in the field.

DUNE SYSTEMS OF DIFFERENT AGE IN THE SOUTHERN HIGH PLAINS

SERIES I

The modern dune movements—principally active dunes and those of late post-Pleistocene or Recent time: (*a*) blowout and elongate-blowout dunes, both active and anchored; (*b*) shrub-coppice dune series; (*c*) active transverse dune series; (*d*) active barcans; (*e*) active isolated transverse dune ridges; and (*f*) areas where active wind scour and sand deposition are too complex and irregular to classify.

a) *Active blowout and elongate-blowout dunes.*—Figure 29, a small-scale copy of the original dune maps, shows in general where the blowouts and other Series I dunes are to be found in that part of

the southern High Plains in Texas, Oklahoma, and New Mexico which was covered by Soil Conservation Service aerial photographs. The areas shown merely indicate where blowouts are common and do not represent individual dunes. No attempt has been made to show the areas of cultivated land which were so badly damaged by wind shortly before and after 1934.

(1) Direction of sand movement.—In most of the area of the southern High Plains of Texas and Oklahoma the direction of movement is now, and has been in the recent past, N. 10°–25° E. The eastern limit of the region in which this direction of modern dune movement prevails is in central Oklahoma. The western limit is found near the New Mexico–Texas boundary. In eastern New Mexico near Clovis and Tucumcari the sand movement today is dominantly N. 40°–50° E. and locally N. 60°–70° E. Whereas this system of blowout dunes (extending N. 40°–70°E. in eastern New Mexico) is now mainly confined to New Mexico, in the time just prior to the "modern" stage a wind with the same effective direction was forming blowout dunes as far east as the eastern boundary of the Texas Panhandle region.

The northern limit of the modern wind (N. 10°–25°E.) or at least the northern limit of its effectiveness as a sand-moving agent, is a broad zone of confused dune forms in southern and central Kansas.

In east-central Nebraska active blowout dunes are moved by strong winds toward S. 20°–25°E. The direction of movement is clear and unmistakable, and there is very little interference by other winds. This southeastward-moving wind gradually becomes less and less effective toward the south.

In a few places, especially near the eastern edge of the southern High Plains in northwestern Oklahoma, the wind is occasionally effective in moving sand N. 10°–40° W. Though winds frequently blow in this direction in central Oklahoma, in northern Texas, and even at the edge of the southern High Plains in western Texas, they are usually so heavily laden with moisture that they have little effect upon sand surfaces. At the edge of the High Plains in northwestern Oklahoma, however, the many variable conditions apparently are just right to permit a small amount of sand movement by southeast winds. Farther west in the High Plains, this same wind is not effective because of its lack of persistency or for other reasons.

(2) Age in years.—These dunes have been forming sporadically as long as the present regimen of prevailing wind direction has existed—at least for several hundred years (cf. later discussion of age under Series III). The rate of their formation has undoubtedly been accelerated by the occupancy of the region by white men.

b) *Active shrub-coppice dunes.*—The location of the main areas of active shrub-coppice dunes cannot be shown in Figure 29. Though such dunes are fairly common, both in small and in large groups, in the southern part of the region investigated, they could be mapped only with difficulty by the methods used in this study. The active coppice dunes move, of course, with the prevailing regional winds. There is no discrepancy, so far as known, between the direction of migration of these dunes and of the blowout dunes in the same locality. Anchored coppice dunes have not been studied sufficiently to determine the direction which they were moved during the last stages of their activity.

c) *Active transverse dune series.*—Figure 29 shows the location of the principal areas of active dunes in the southern High Plains. All types of active dunes are grouped together, especially the transverse dune series and active blowouts. Only those dune areas have been shown, however, which were apparently active before the region was cultivated. It would be futile to attempt to show the numberless localities of wind erosion and sand deposition which resulted from this cultivation. Hence Figure 29 does not show the location of areas of isolated transverse-dune ridges and barcans.

The main localities of transverse dune series are (1) the north side of the Canadian River Valley, northeast of Amarillo, Texas, and (2) in the "Protales" Valley southeast of Clovis, New Mexico. The prevailing direction of sand movement is best understood by examination of Figure 29. In a general way the movement is now toward the northeast and is in harmony with the direction shown by active blowouts and other types of dunes.

No district within the southern High Plains contains transverse dune series with the ideal symmetrical development, though some on the north bank of the Canadian River Valley are a rough approximation to this condition. Were all the causal factors except wind direction perfectly constant, the most symmetrical dunes of this type would be found where the winds have the most nearly constant

direction. The nature and topographic position of the predominant sand supply (a broad, flat, but shallow sand supply, such as a dry lake bottom, contrasted with a narrow and continually replenished sand supply, such as a sandy river flood plain), the relative humidity, persistency, and velocity of the principal conflicting winds, are important factors in determining the exact degree of dune symmetry which will develop.

(1) Age in years.—The existing transverse dune series are very recent in age. It is doubtful if they originated more than a few hundred years ago, and perhaps their age is not more than one hundred years. There is no doubt that different small areas of transverse series have been in almost continuous existence for several thousands of years, but no one series existed long. The special conditions which brought them into existence—for example, the sudden shifting of a low-water channel—were of temporary nature. They were without doubt increasing in area, until the United States Department of Agriculture introduced a sand-anchoring program in the High Plains; whether or not these dunes are still increasing in size is uncertain. Once a transverse series begins to yield to the advance of grasses, its decline as a dune series may be rapid; in its place will be left an anchored surface pitted with blowouts.

Transverse dune series are not known to the writer in the anchored state, and it seems evident that none will be found without the aid of man in introducing vegetation to take control of the surface with unnatural rapidity.

d) Active barcans and isolated transverse dune ridges.—These dunes are common in that part of the southern High Plains subjected to the worst erosive conditions during the past decade. The barcans are not so symmetrical as those found in Peru but are more rounded and possess shorter wings. They usually arise from the breaking-up of the transverse ridges after the first few seasonal changes in wind direction. The direction of movement is in harmony with that of the active blowout dunes, shrub-coppice dunes, and transverse dune series, though the localities where they occur are not shown on Figure 29 because of the intimate way in which they are related to cultivated fields. As in the case of the transverse series, these dunes do not occur in the anchored condition save where man has intervened in re-establishing the grass or shrub cover.

e) Summary of the regional extent and direction of present-day active sand movement.—

1. In eastern New Mexico, toward N. 40°–70° E.

2. In most of the southern High Plains of Texas and Oklahoma, toward N. 10°–25° E.

3. In a few places in northwestern Oklahoma the direction of predominant sand movement is toward the north and even toward the northwest.

Series I active dunes of different kinds are illustrated by Figures 8, 12, 14, 15, 16, 25, 28. They are present, though more obscure, in Figures 18, 19, 22, 23. Series I anchored blowouts are clearly shown by Figures 16 and 19.

SERIES II

Series II is separated from Series I on the basis of direction of movement and difference in age. It consists of anchored blowouts, anchored elongate-blowouts, and perhaps occasional imperfect wind-drift dunes. It may be found by means of aerial photographs in the southern High Plains at most of the localities where sand deposits of considerable thickness occur.

Without the aid of detailed maps showing the dune sequence at many different localities, the existence of a Series II group of dunes would not be evident. It would be clear, of course, that there were blowout dunes of different ages, though the manner in which they transect one another would appear to be very intricate. Using the maps, however, it is apparent that prior to the modern Series I dunes, the prevailing sand-moving wind blew rather consistently from a slightly different direction.

The main localities of Series II dunes are shown in Figure 29, together with the direction of former movement.

The direction of N. 40°–70° E. is still the prevailing direction even today in part of northeastern New Mexico and the westernmost part of Texas. It is no longer the direction of prevailing sand movement farther east in the High Plains, however, where Series II dunes are more obscure than either Series I or Series III.

SERIES III

The dunes of Series III differ from those of Series II in orientation, in degree of development, and in age. They are similar in

kind. They compose all known varieties of the blowout form though they are now, of course, anchored by vegetation. Series III dunes, it will be remembered, are older than Series II and have been separated from them because the younger dunes have definitely invaded and transected anchored dunes of the older series. The two series are, however, gradational into one another, especially near Clovis in eastern New Mexico and the adjoining part of Texas. Farther northeastward they are more sharply separated. The outstanding characteristic of Series III is the presence of anchored windrift dunes and of very elongated anchored blowouts. Though active elongate-blowout dunes of different orientation from those of Series III are now in process of formation in near-by regions, windrift dunes as well developed as the typical windrifts of Series III are not being formed today.

Location and extent of Series III dunes.—Figure 30 shows the location of the principal areas of windrift dunes and elongate blowouts as well as the direction of dune migration. The outstanding examples of the windrifts of this series are: (1) the Canadian River dune area in Roberts and Hemphill counties, Texas, and (2) the area in southern Lea County, in southeastern New Mexico.

Elongate-blowouts of this same series are found in the two districts mentioned above and also in the Portales-Muleshoe dune area south of Clovis, New Mexico.

The windrifts are developed best where sand was deepest and where wind was most constant in direction. The windrift form apparently becomes longer and straighter with increasing distance northward.

Figure 31 shows a locality in Hemphill County, Texas, where Series I and perhaps Series II dunes have invaded and destroyed windrifts belonging to Series III.

The direction of movement of the windrift and elongate blowout dunes of Series III shows that the prevailing effective wind of that time moved approximately S. 70° E. though it varied some 10° to either side of this direction. The windrifts of the Canadian River area and those south of Hobbs in Lea County, New Mexico, are remarkably parallel in spite of the fact that the distance between the two localities exceeds 300 miles. The elongate blowouts of Series III in the Portales Valley also agree well with the direction of

S. 70° E., though these are more variable in direction than the windrifts. This suggests that the dunes of Series III may have been formed over a considerable span of time, during only a part of which were the winds sufficiently persistent to form the long straight windrifts. The conditions near Clovis further show that blowouts were forming there while the prevailing effective wind was shifting during the interval of time between the formation of Series III and Series II.

a) Age in years.—There is no known way of measuring the span of time which has elapsed since a strong and persistent wind, blowing approximately S. 70° E., formed the windrifts and associated elongate blowouts. It is fairly evident, however, that they were formed before the time of origin of the highest preserved shorelines around the old lake basins between the western escarpment of the southern High Plains and the Rocky Mountains in central New Mexico. Extinct Lake Estancia, and other extinct lakes of smaller size to the southeastward, very commonly possess considerable deposits of sand on their northeastern shores. Such deposits are, however, usually absent on the southeastern side. This would indicate that the Series II wind (approximately toward N. 40°–70° E.) was the prevailing wind at the time that the lakes occupied their highest shores and that Series III, therefore, was formed before this time. Series III dunes are, of course, known to be older than Series II dunes from their mutual relationships in areas where both series are still preserved.

Antevs[32] has estimated that Lake Estancia stood at the level of its highest preserved shoreline some 15,000 years ago. Though this figure is quite uncertain, it is still a starting-point, and the approximate age of the dune series discussed in this paper will be based tentatively upon it.

Series III—formed more than 15,000 years ago.
Series II—formed between 15,000 and perhaps 5,000 years ago.
Series I—formed during the last 5,000 (?) years.

The date—5,000 years in the past—which may divide Series II from Series I is of the most tentative nature. It is all the more uncertain because Series II and Series I dunes are not sharply divided

[32] Ernst Antevs, "Age of the Clovis Lake Clays," *Proc. Acad. Nat. Sci. Phila.*, Vol. LXXXVII (1935), pp. 310–11.

in direction except at a few localities well to the east in the High Plains.

The unique nature of the Series III windrift dunes can hardly be overemphasized. Well-developed windrifts of the same type are not now forming at any known locality within the interior of North America. It is doubtful, furthermore, if they are to be found in the active condition about the coasts of North America. At least, all known active-dune localities studied by the writer[33] show forms, such as source-bordering lee dunes, elongate blowouts, transverse dune series, and others, but do not show genuine windrifts approaching in elongation those of the Canadian River dunes in northern Texas.

b) Variations of windrift form in Series III.—Several variable factors apparently affected the form of the windrift; chief among these was the variation in size of the blowout area as it moved downwind. For example, a blowout migrating downwind and maintaining constant size, produced the simple case of the two straight parallel ridges, shown in Figure 22. Migrating blowouts which gradually diminished in size, however, produced certain forms shown in Figure 23. An increase in blowout diameter, followed by a decrease, resulted in other irregularities which may also be found in Figure 23.

c) Dune series of questionable age.—Near the town of Plains in northern Yoakum County, Texas, and perhaps bordering southwestern Oklahoma in Wheeler and Collingsworth counties, Texas, are some obscure elongate-blowout and possibly windrift dunes which appear to extend S. 40°–70° E. It seems probable that these thoroughly anchored features represent dunes older than Series III because of their relatively large size and their position near well-known areas of Series III windrifts. If the Yoakum County dunes are younger than Series III, it is difficult to see why this wind (S. 55°–70° E.) did not disturb the Series III dunes to any noticeable extent. The small size of these Series IV (?) dune areas is in keeping with the assumption that they are older than Series III and were nearly everywhere destroyed during the relatively intense conditions that prevailed when the windrifts of Series III were being formed.

[33] Long Island, the coast of Virginia, North and South Carolina, Georgia, northern Florida, Louisiana, Texas, and California south of San Francisco.

In the Canadian River dune area in northern Texas the windrift ridges are commonly scarred by a series of small blowouts which developed in the crests of the ridges. The sand from these small blowouts was blown toward the southeast—approximately S. 45°–60° E. It is a question whether these represent (1) a distinct climatic change after the development of the windrifts of Series III or (2) the effect of occasional strong northwest winds working on exposed ridges either at the same time that the windrifts were forming or possibly during the time of the Series II dunes. The first explanation is probably the correct one. There is, however, a lack of definite information showing these to be earlier or later than dune Series II.

d) Unclassified dunes.—There are several small areas where blowout and elongate-blowout dunes of unusual direction and indeterminate age may be found. These are apparently entirely local and are considered to have been rapidly formed in response to strictly local conditions, such, for example, as the sudden and local lowering of the ground-water table through stream meandering or sinkhole drainage changes. Though these erratic dunes exist, they do not affect the validity of the dune systems which are here defined.

ACKNOWLEDGMENTS.—Credit is gratefully given to the following individuals and organizations for assistance of various kinds: Dr. C. W. Thornthwaite, of the Soil Conservation Service, Section of Climatic and Physiographic Research, for generous support of the study; Mr. E. R. Polley, of the Fairchild Aerial Surveys in Los Angeles, for permission to study the High Plains photographs during the process of their assembly, a time when such permission meant no little inconvenience to the company; Dr. Bruno Klinger and Dr. Nieschmidt, of the Albuquerque office of the Soil Conservation Service, for their assistance in conducting field trips in Arizona and New Mexico; and Mr. Claude Fly, of the Amarillo office of the Soil Conservation Service, for assistance in making field excursions in the southern High Plains. Many others as well have assisted in the study.

Van Keuren–Shippee, New York City

FIG. 1.—Barcan dunes moving northward (toward the right) across an alluvial fan between Mollendo and Arequipa in southern Peru. These dunes are 10–20 feet high and are more than 100 feet long. The crescent opens downwind. Note that the dunes are free from vegetation and that they rest upon a base, which, while it may be sandy, is not loose sand. They are said to move approximately 60 feet per year.

Van Keuren–Shippee, New York City

FIG. 2.—Two trains of barcan dunes move northward (toward the upper right). across an alluvial fan between Mollendo and Arequipa, Peru. The train at the left arises from a longitudinal dune which lies to leeward of a bedrock hill. For a short distance downwind from the source these dunes become larger and more widely scattered. The train at the right has its source beyond the lower edge of the picture. Small dunes move faster than large ones and thus frequently lose their identity by merging with the larger dunes.

Van Keuren–Shippee, New York City

FIG. 3.—A complex train of barcan dunes between Mollendo and Arequipa, Peru. The unsymmetrical shape of these dunes is interpreted as due to a recent shift of wind slightly across its original direction. The large irregular dune at the right resulted from unification of several smaller dunes. Exact scale indeterminate.

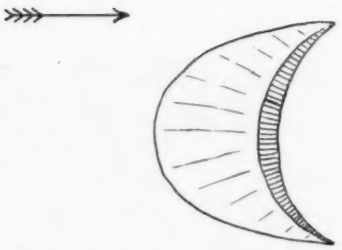


FIG. 4.—Probable barcan form produced by gentle winds of constant direction

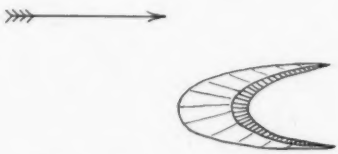


FIG. 5.—Probable barcan form produced by strong winds of constant direction

FIG. 6.—With constant wind direction it is probable that the strongest known winds would produce, from a pre-existing pile of sand, not the barcan form but that of a longitudinal dune.

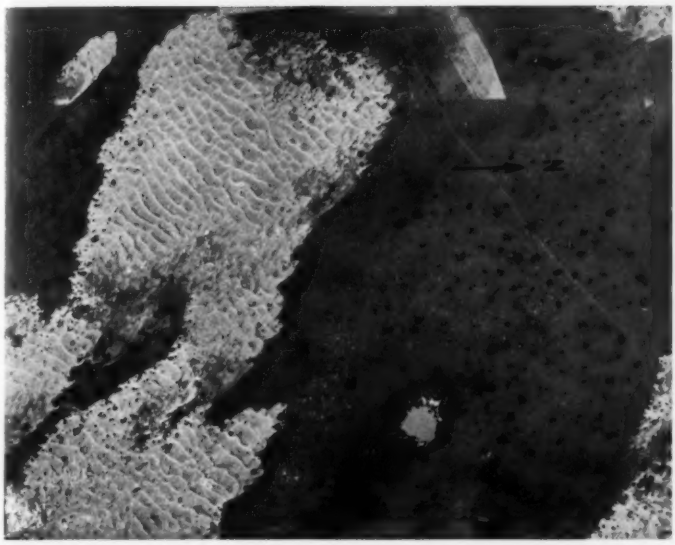
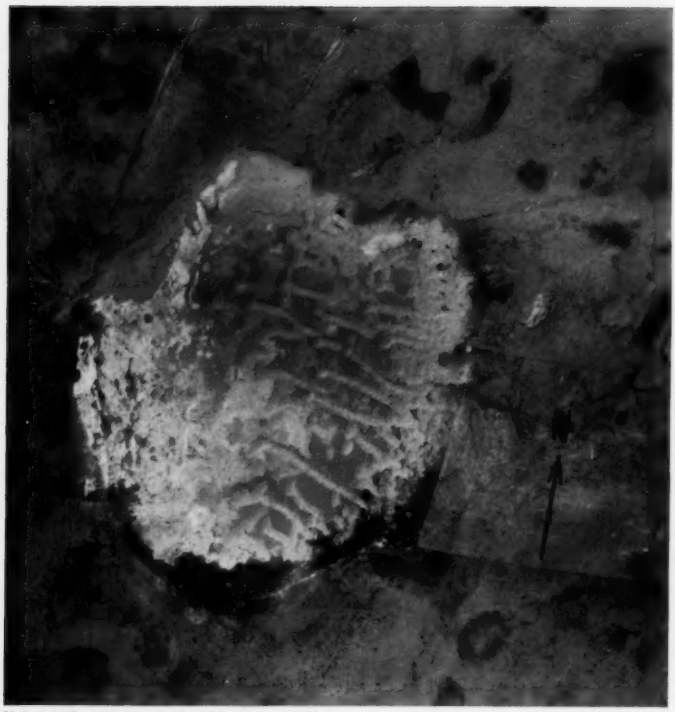


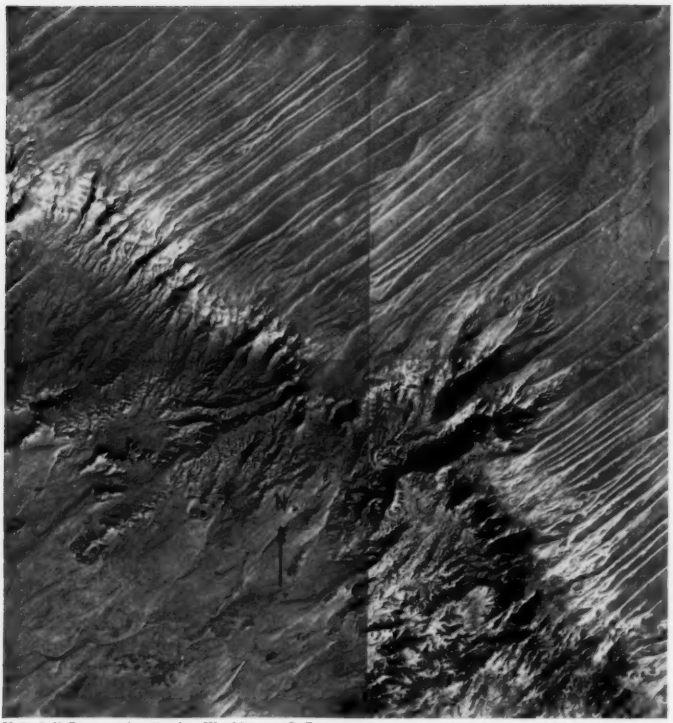
FIG. 7.—Vertical aerial photograph of a transverse-dune series in Duval County, southern Texas. The prevailing effective wind moves toward the northwest. Long dune ridges, which exist in an approximately parallel series, are alined perpendicularly to this wind. The gray surface is covered by vegetation. The area shown is approximately 2½ square miles.



U.S. Soil Conservation Service, Washington, D.C.

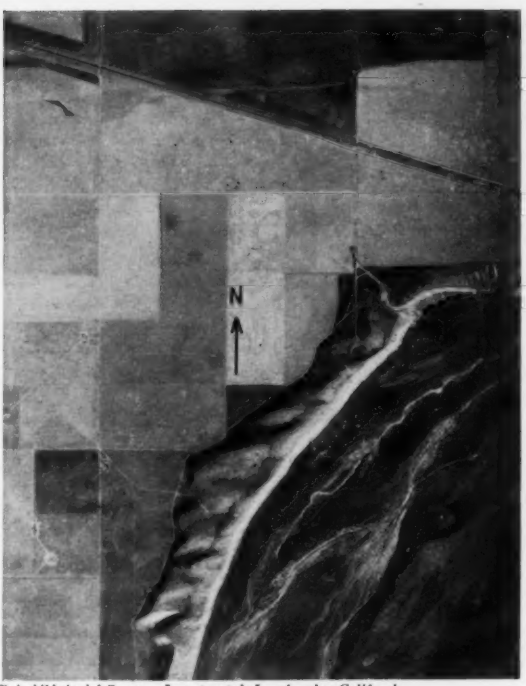
FIG. 8.—Vertical aerial photograph illustrating isolated transverse-dune ridges formed by an effective wind moving prevailingly N. 20° E. The transverse ridges do not form a regular series but are unevenly spaced. Prior to the formation of the dunes the thin sandy soil was damaged by cultivation. The area shown is approximately 3 square miles.

FIG. 9.—Vertical aerial photograph showing narrow elongated dune ridges (longitudinal dunes) extending southeastward on the lee side of bedrock hills. Superstition Mountains, west of Brawley, Imperial County, California. A group of imperfect barcan dunes have arisen downwind from the longitudinal dunes. The area shown is approximately $4\frac{1}{2}$ square miles.



U.S. Soil Conservation Service, Washington, D.C.

FIG. 10.—Vertical composite aerial photograph illustrating narrow longitudinal dunes in north-central Arizona. These dune ridges on the summit of the Moencopi Plateau extend downwind, approximately N. 50° E., back from the edge of the escarpment. Soft and easily eroded Jurassic sandstone underlies the margin and surface of the plateau which is approximately 6,000 feet above sea-level. The lowlands at the lower left are only 4,500 feet high. Note that the sand ridges are situated chiefly in the lee of promontories of the cliff face and are absent to leeward from the canyons. The dunes are thus to be classified as lee dunes. A meager sand supply and winds of a high average velocity and of very constant direction characterize this plateau. Vegetation has partially anchored these dunes. The area shown is approximately 23 square miles.



Fairchild Aerial Surveys, Incorporated, Los Angeles, California

FIG. 11.—Vertical aerial photograph illustrating a source-bordering lee dune on the west side of a stream flood plain near Bakersfield, California. The ridge is a unit despite the irregular hills and swales which compose it. Cold air flowing under the influence of gravity down the western slope of the Sierra Nevadas has apparently been responsible for the formation of this dune. It is largely anchored by vegetation. The area shown is approximately $5\frac{1}{2}$ square miles.

Aero Exploration Company, Tulsa, Oklahoma

FIG. 12.—Vertical aerial photograph of the Cimarron River and three source-bordering (or lee-source) dune ridges near Waynoka, Woods County, Oklahoma. The most recent source-bordering dune is the smallest of the three. It is very near the lee (northeastern) bank of the bare channel bottom. The older dune ridges are larger, more complicated in form, and partly anchored by vegetation. The three source-bordering ridges mark former positions of the northeastern bank of the bare sand plain, which has shifted southwestward in a spasmodic manner. Older anchored dunes of diverse origin, including several which show the effects of this same northeastward moving wind may be seen in the northeastern part of the area. Blowout dunes, indicated by *A*, *B*, *C*, and *D*, (see p. 123) are forming at the present time under the influence of a persistent wind moving N. 20° E. The area shown is nearly 4 square miles.

Spence Air Photos, Los Angeles, California

FIG. 13.—Source-bordering lee dune looking northwestward near Hyperion and El Segundo, Los Angeles County, California. The large size of the ridge is evident in comparison with the size of the houses at the right. The obvious fact that this sand has come from a narrow beach is an indication that the ridge is quite old. Though the sand is chiefly anchored by vegetation, in a few places it is still in motion.

FIG. 14.—Shrub-coppice dunes recently developed upon a thin sandy soil near Carlsbad, New Mexico. Looking northeastward. Note that the near side of the center dune is undergoing wind scour, and the shrub is being undermined and killed. On the far side the mesquite grows vigorously.

FIG. 15.—Shrub-coppice dune near Carlsbad, New Mexico. Looking northwestward. Note that the southwestern (left) side of the large dune is nearly bare of vegetation. The northeastern (right) side is a vigorously growing clump or coppice of mesquite bush. Dunes of this type migrate very slowly, keeping all the while their protective growth of vegetation.

U.S. Soil Conservation Service, Washington, D.C.

FIG. 16.—Vertical aerial photograph of blowout dunes, both active and anchored, near Higgins, Lipscomb County, Texas. The bare sand of the active dune shows white; surfaces anchored by vegetation are gray. The area shown is approximately 5 square miles.

Abrams Aerial Survey Corporation, Lansing, Michigan

FIG. 17.—Elongate-blowout dunes on the eastern shore of Lake Michigan near Grand Haven. Looking southward. Most of the dunes have been anchored by forest, though a few are active at the present time. There is a suggestion that these dunes are alined in ranges which may be related to earlier and higher levels of the lake. They are developed from a lee-source dune complex.

FIG. 16.—Vertical aerial photograph of blowout dunes, [illegible]
The bare sand of the active dune shows white; surfaces anchored by vegetation are gray. The area shown is approximately
5 square miles.

U.S. Soil Conservation Service, Washington, D.C.

FIG. 18.—A series of elongate-blowout dunes in Curry County, New Mexico. Most of these blowouts are anchored by vegetation and show by their form that the sand was moved southeastward and eastward—a direction of movement that is practically unknown in the presently active dunes of the same district. The area shown is approximately 6 square miles.

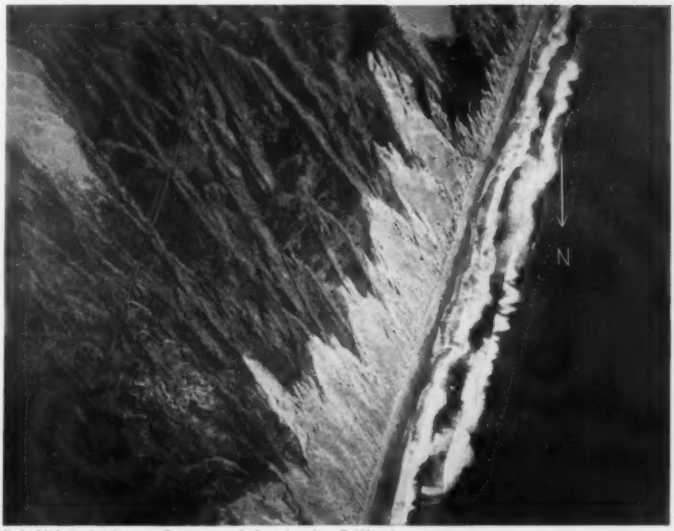
vegetation and show by their form that the sand was moved southeastward. Such dunes are practically unknown in the presently active dunes of the same district. The area shown is approximately 6 square miles.

U.S. Soil Conservation Service, Washington, D.C.

FIG. 19.—Vertical aerial photograph illustrating elongate-blowout and windrift (?) dunes in Roberts County, northwestern Texas. The hairpin shape of these dunes shows that the direction of movement was approximately N. 20° E. Though the dunes are largely anchored, a cluster of active blowouts, shown by white surfaces of bare sand, is today moving in the same direction. Cultivated surfaces of flat land as well as steep-sided small valleys are shown at the right. The area is approximately 6 square miles.

Spence Air Photos, Los Angeles, California

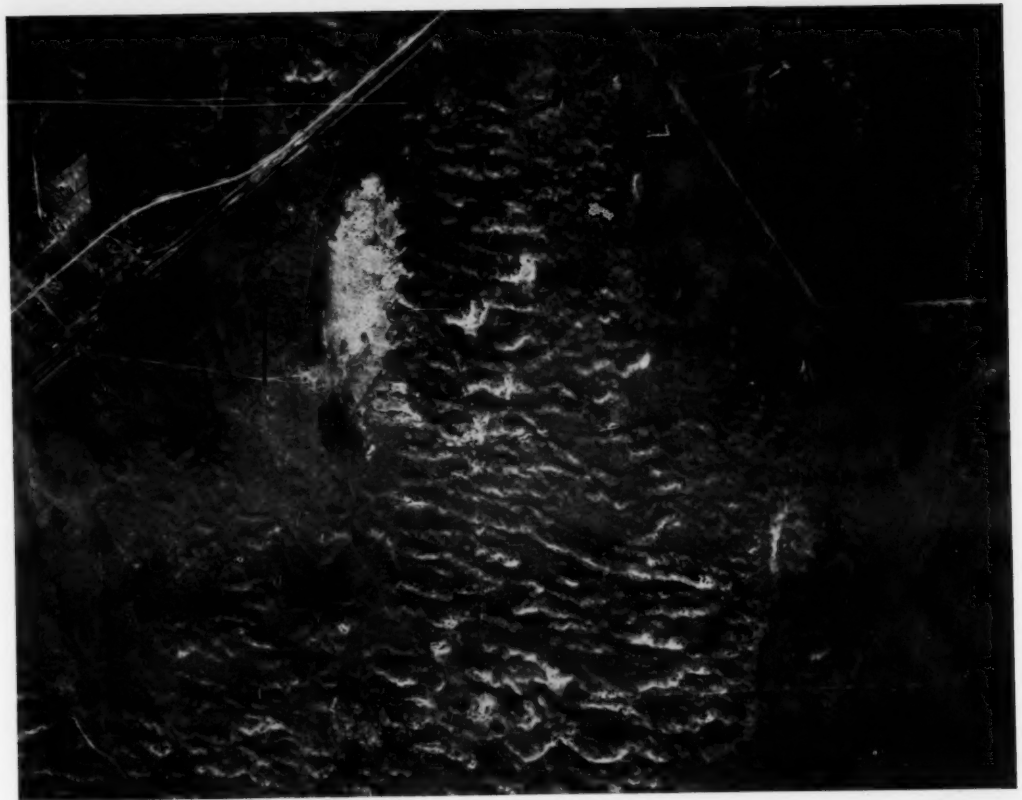
FIG. 20.—Anchored elongate-blowout sand dunes are shown in the foreground on the landward side of an active transverse dune series near Pismo Beach, San Luis Obispo County, California. The elongate blowouts are much older than the active dunes and have yielded up their sand to renewed movement, probably through influence of climatic changes.



Fairchild Aerial Surveys Incorporated, Los Angeles, California

FIG. 21.—Vertical aerial photograph showing a well-developed series of anchored elongate-blowout dunes near Purisima Point, Santa Barbara County, California. The sand of the active dune areas, though partially derived from the beach, has also to some extent been reclaimed from the older dunes, no doubt through climatic change. The Southern Pacific Railroad is shown at the left.

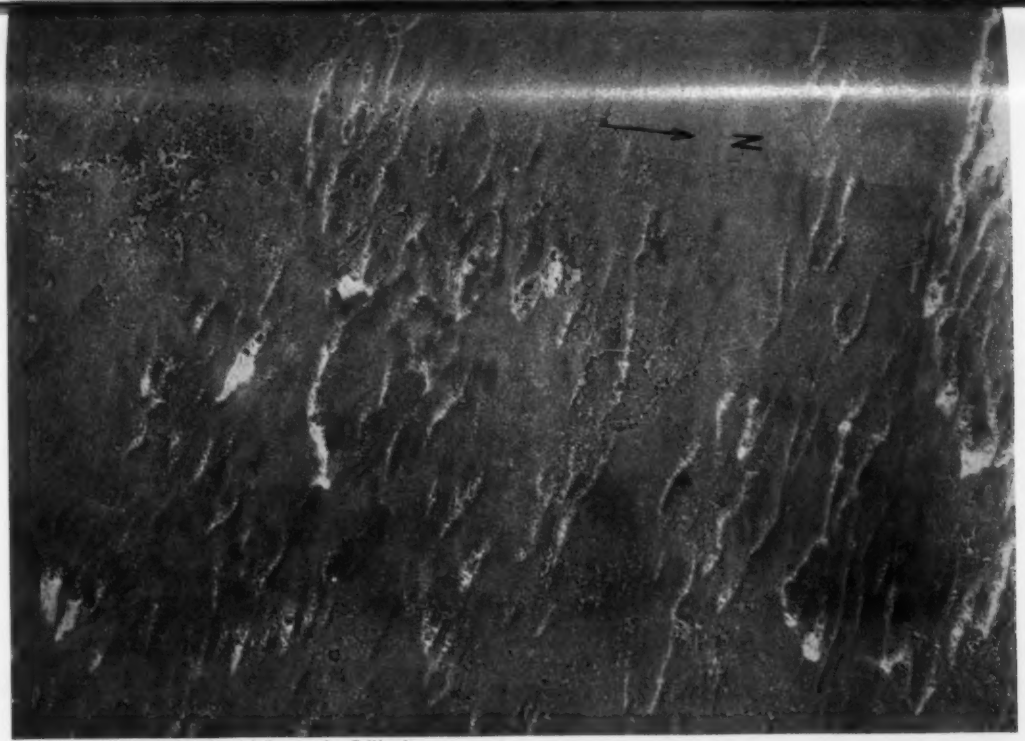
verse dune series near Pismo Beach, San Luis Obispo County, California. The elongate blowouts are much older than the active dunes and have yielded up their sand to renewed movement, probably through influence of climatic changes.



U.S. Soil Conservation Service, Washington, D.C.

FIG. 22.—Vertical aerial photograph showing the remnants of an old series of windrift dunes at Glazier in Hemphill County, northwestern Texas. One well-preserved dune shows the typical paired ridge. The direction of its former migration was S. 70° E. A number of scattered blowouts both large and small show that sand is moving today toward the northeast. Old dunes which have migrated toward the southeast are described in Part II in this paper as the dunes of Series III. Dunes of this series are prevailingly windrifts or elongate blowouts; they point to the former existence of winds of greater velocity or more constant direction, or both, than winds of the present. The area shown is approximately 6 square miles.

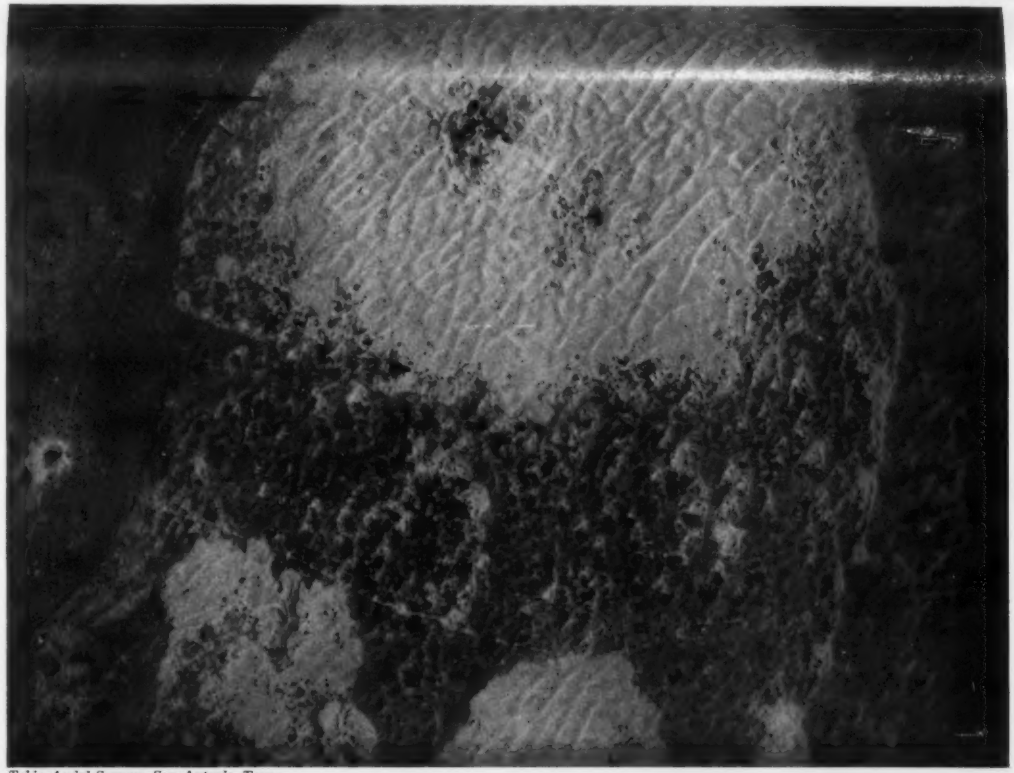
of this series are prevailingly windrifts of elongate blowouts, many
or more constant direction, or both, than winds of the present. The area shown is approximately 6 square miles.



Fairchild Aerial Surveys Incorporated, Los Angeles, California

FIG. 23.—Vertical view illustrating anchored windrift and elongate-blowout sand dunes east of Carlsbad in Lea County, New Mexico. The paired ridge is fairly common, as is the hairpin-shaped type of ridge with the opening facing northwestward—the upwind direction at the time of dune formation. Modern sand movement is directed northeastward and thus far has been of small volume in comparison to that which has gone before. At the time of their formation these windrift dunes were formed by an effective wind blowing approximately S. 70° E. The area shown is roughly $3\frac{1}{2}$ square miles.

FIG. 24.—The drawings illustrate the connection between barcan form and three types of cross winds. The arrows are vectorial in the sense that they show the direction and relative velocity of the conflicting winds.



Tobin Aerial Surveys, San Antonio, Texas

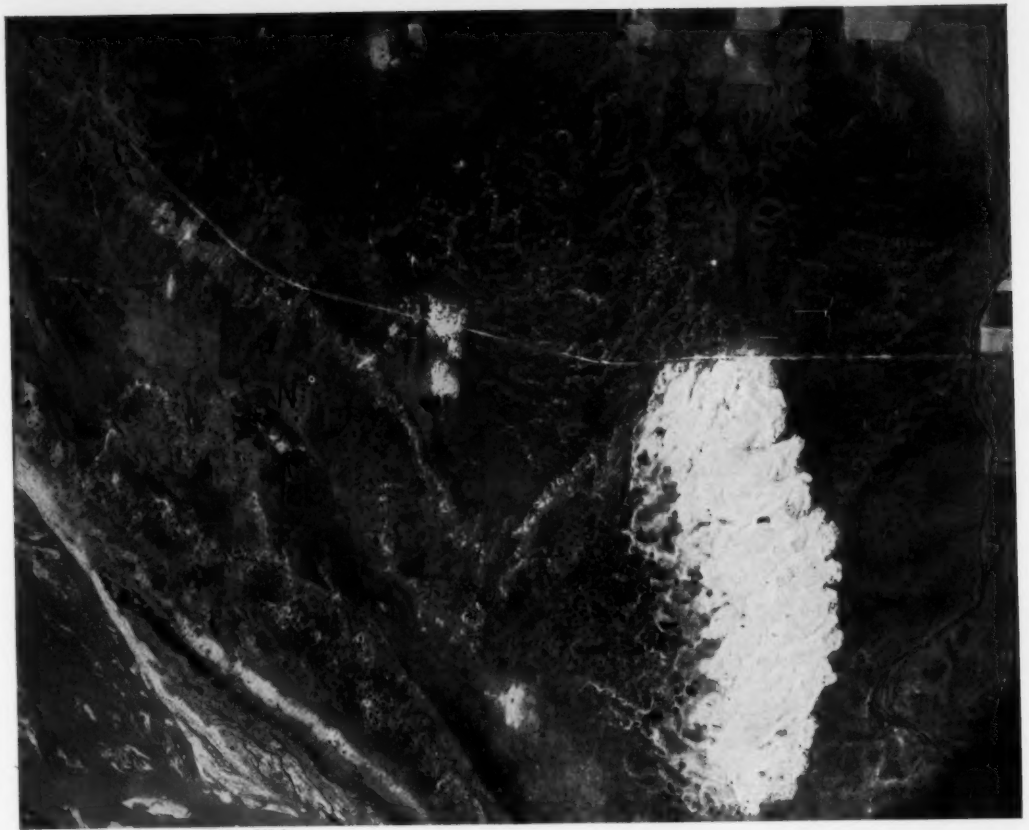
FIG. 25.—Vertical aerial photograph showing at least two intersecting sets of transverse dune series near the Pecos River in Crane County, western Texas. The principal series extends northeast-southwest. This illustrates a type of dune topography which may be described as "peak and fulje." The area shown is approximately 3 square miles.

Spence Air Photos, Los Angeles, California

FIG. 26.—A surface of complex sand dunes formed by conflicting winds. Looking northwestward across the Imperial Valley dunes from a point a few miles west of Yuma, Arizona. The surface is perhaps best described as "intersecting transverse dune series," though it is apparent that more than two intersecting sets may be present. It is impossible to detect the *order* which usually exists on surfaces of this nature without the use of vertical aerial photographs. The ground observer is usually lost in a maze of topographic peaks, basins (fuljes), and saddles. In certain places where the sand supply is meager, barcan dunes have formed.

Fairchild Aerial Surveys Incorporated, Los Angeles, California

FIG. 27.—Vertical aerial photograph of oblique longitudinal dunes near Hanford in Benton County, southeastern Washington. The surface is almost entirely anchored by vegetation. It is evident that longitudinal dunes, together with some blowout dunes, have been formed by an effective wind moving toward the northeast by east. At the same time, or later, these dunes were attacked and modified by winds moving more nearly toward the north. The dynamics of the formation of oblique longitudinal dunes is still uncertain. The area shown is approximately 3 square miles.



Aero Exploration Company, Tulsa, Oklahoma

FIG. 28.—Vertical aerial photograph showing a small area of active complex dunes on the north bank of the Cimarron River near Waynoka in Woods County, Oklahoma. More than half of this photograph appears also in Figure 12. Modern wind activity is destroying the complex surface of older, anchored dunes by means of wind scour and the formation of modern blowouts. Advancing transverse dune ridges are burying the old surface beneath them. The areas of the active sand surface and the entire photograph are approximately ½ and 5 square miles respectively.

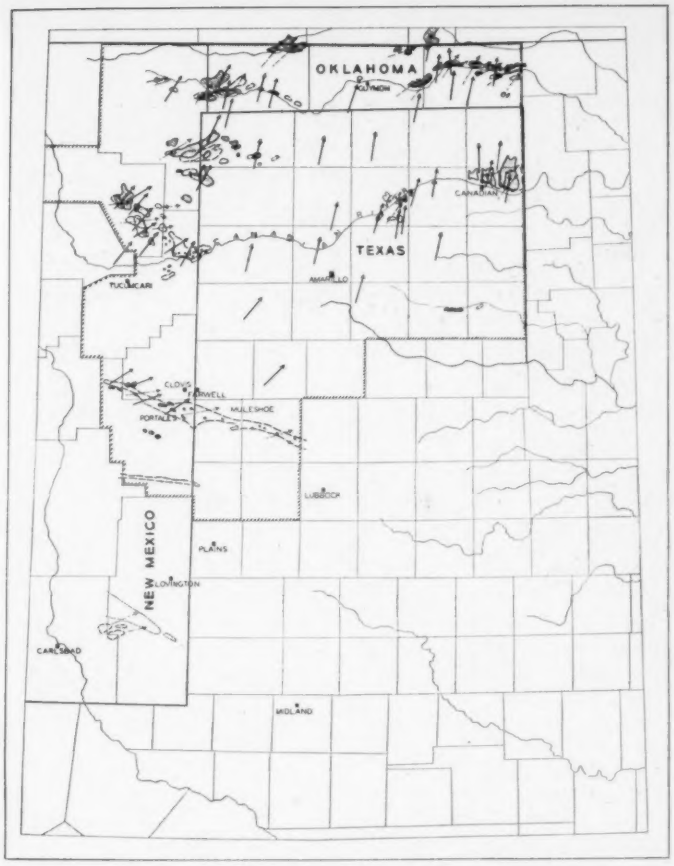


FIG. 29.—This map shows the location of the principal areas of active or modern (Series I) sand dunes, and also of the Series II anchored dunes, in a portion of the southern High Plains. It also shows the direction of the prevailing sand-moving wind at the two different times. Series I is shown by shaded areas and heavy, solid arrows; Series II by unshaded areas and dashed arrows. *Series I Dunes:* Most of these dune areas existed before the white man came; no attempt has been made to show the dunes which have developed during the last two decades as a result of cultivation. The areas include principally blowout dunes, both anchored and active, as well as transverse dune series. Shrub-coppice dunes are not shown, nor are the isolated transverse dune ridges and barcans of the cultivated areas. Arrows point with the prevailing effective sand-moving wind. *Series II Dunes:* These dunes are now entirely anchored. They are chiefly blowouts, elongate blowouts, and imperfect windrift dunes. Other types of sand dunes (of the bare sand-hill type) doubtless existed but were destroyed during the process of becoming anchored by the growth of vegetation. These dunes were formed under a prevailing, effective, sand-moving wind noticeably different in direction from the present wind, especially near the eastern edge of the plains. A dune area of doubtful significance and boundaries is shown in southeastern New Mexico. (The irregular area outlined in hachures is the territory covered by Soil Conservation Service areal photographs.)

blowouts. Advancing transverse dune ridges are burying the old surface beneath them. The areas of the active sand surface and the entire photograph are approximately 3 and 5 square miles respectively.

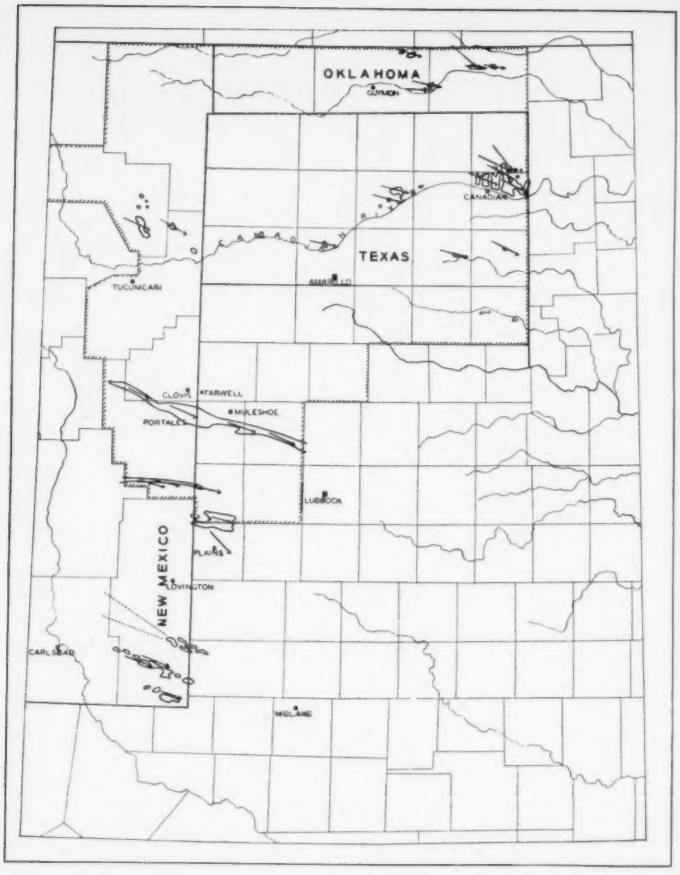
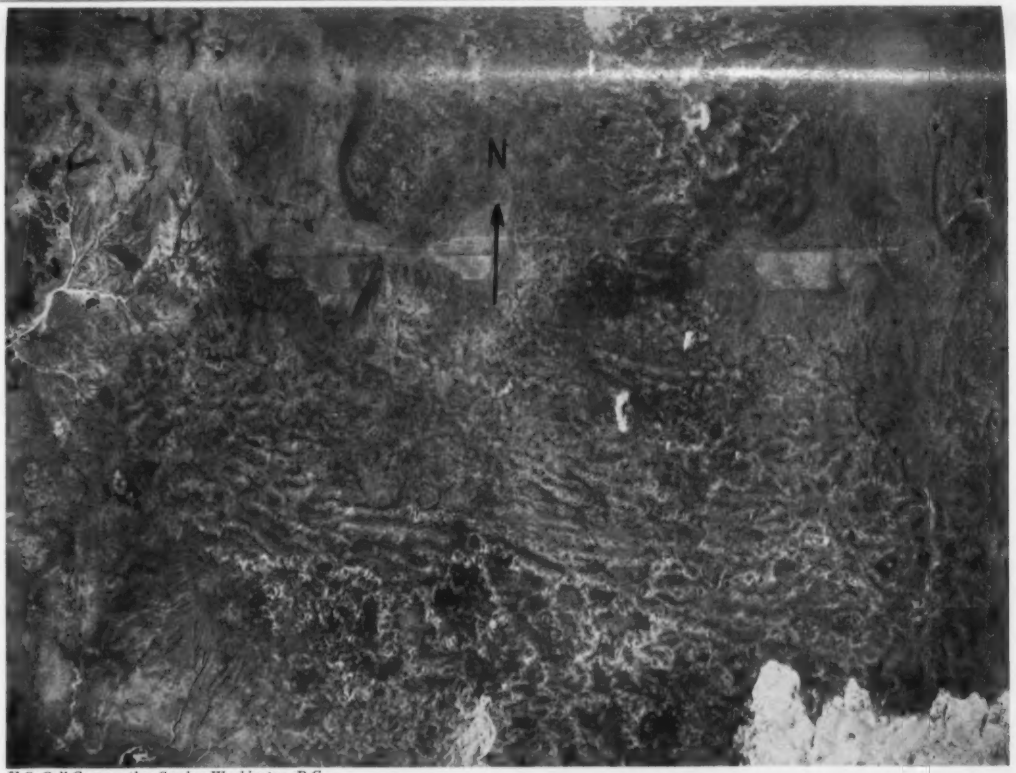


FIG. 30.—This map shows the location of the principal areas of Series III anchored sand dunes in a portion of the southern High Plains. They are chiefly elongate-blowout and windrift dunes which persist in various stages of preservation depending upon the number of more recent dunes that have transected them. Other types of sand dunes (of the bare sand-hill type) doubtless existed but were destroyed during the process of becoming anchored by the growth of vegetation. These dunes were formed under a prevailing, effective, sand-moving wind (shown by arrows) very different in direction from that of modern time. The relationship of sand bodies to the highest shorelines of dry lakes west of the High Plains seems to show that these dunes were formed before the last high-water stand of the lakes. Antevs has estimated these shores to be some 15,000 years old. The elongation of anchored dune ridges, possibly older than Series III dunes, is shown near Plains in Yoakum County, Texas. A "series" of anchored blowouts, younger than Series III and possibly older than Series II, is indicated by arrows pointing S. 40°–50° E., at two points north of the Canadian river. A dune area of doubtful significance is shown in southeastern New Mexico.



U.S. Soil Conservation Service, Washington, D.C.

FIG. 31.—Series III windrift dunes which have been invaded and partially destroyed by Series I (modern) dunes, both anchored and active. The locality is northwestward from Gem, Hemphill County, northern Texas. It is clearly evident that Series III and Series I dunes are of different age. The area shown is approximately 5 square miles.

DILATION AND REPLACEMENT DIKES[1]

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University of Washington

ABSTRACT

A detailed study of many dikes in the Pacific Northwest, ranging from basalt and diabase to aplite and pegmatite, shows evidence for two contrasting mechanisms of dike formation: (1) dilation concomitant with magmatic injection and (2) replacement. Criteria for the recognition of both dilation and replacement dikes are presented. For the replacement type, transitional facies are emphasized, since in the final stage definite characteristics of an earlier stage may be partially or wholly obliterated. The implications of simple magmatic injection are very different from those of the complex processes of metasomatism.

INTRODUCTION

Dikes are common in many parts of the Pacific Northwest, and in some localities favorable exposures permit detailed field studies. Probably most of these dikes have been formed by magmatic injection, but the field and microscopic characteristics of some suggest a more complex origin, which the writer attributes to metasomatic replacement, and these are called "replacement dikes." In order to make a clear distinction, those that can be explained by the classical interpretation of the dilation of an initial fissure concomitant with the injection of magma are here referred to as "dilation dikes."

DILATION DIKES

Perhaps the most striking dilation dikes in this region in point of numbers and size are the basalt and diabase dikes of Tertiary age. They form mappable units in the Mount Stuart region of Washington[2] and also are abundant in the Blue Mountains of northeastern Oregon and in the western part of Idaho.[3] They were the feeders for

[1] Presented at the summer meeting of the Geological Society of America at Berkeley, California, August, 1939.

[2] G. O. Smith and F. C. Calkins, "Snoqualmie Folio," *U.S. Geol. Surv. Atlas 139* (1906); Smith, "Mount Stuart Folio," *U.S. Geol. Surv. Atlas 106* (1904).

[3] W. Lindgren, "Gold Belt of the Blue Mountains of Oregon," *U.S. Geol. Surv. 22nd Ann. Rept., 1900–1901*, Part II, pp. 561–776; C. P. Ross, "Geology of Part of the Wallowa Mountains," *Oregon Dept. Geol. and Min. Industries Bull. 3* (1938); Warren D. Smith, "Geologic Reconnaissance Map of the Central Portion of the Wallowa Mountains," *Oregon Dept. Geol. and Min. Industries* (1938); Lindgren, "The Gold and Silver Veins of Silver City, DeLamar and Other Mining Districts in Idaho," *U.S. Geol. Surv. 20th Ann. Rept., 1898–99*.

the successive flows that make up the Miocene Columbia River lavas and in the Mount Stuart region of early Tertiary flows, and in some localities the actual merging of dike and flow may be seen.[4] Many of these dikes are as much as 50 feet in width and have been traced for several miles. Although single dikes are most common, multiple dikes do occur and may be recognized by their respective chilled borders. Chilled selvages are readily noticeable features of most of the dike feeders of the Columbia River basalts, whereas coarser-grained textures prevail in the central portions of the dikes.

The displacement caused by these dikes is well shown at Cornucopia, Oregon, where they intersect the gold-quartz veins.[5] From the standpoint of mining geology, the most important effect of these later basalt and diabase dikes is the structural one of offsetting the veins by widening of the dike fissure (Fig. 1). Since in most cases the only movement has been separation in a direction normal to the strike of the dike, it is a comparatively simple matter to measure the amount and direction of offset. In a few instances where there has been a lateral movement along the walls of the fissure, this simple relation will not hold; and, unless the magnitude and the direction of the movement are known, the amount of offset is indeterminable.

Along the Columbia River in central Washington there are several localities where pre-Tertiary rocks have been exposed, and here numerous dikes are to be found. These dikes represent a wide variety in composition with perhaps a predominance of pegmatitic, aplitic, and granophyric types, and a lesser number of lamprophyres.[6] Many of these dikes offset earlier dikes or veins, and they are attributed to magmatic injection with concomitant dilation.

In the Wallowa Mountains in the vicinity of Cornucopia, some aplitic and pegmatitic dikes and veins have the field appearance of filled gash fractures, and some exhibit intricate contortions similar to ptygmatic folding. The suggestion that they are filled fissures appears to be confirmed by a study of thin sections which commonly

[4] R. E. Fuller, "The Closing Phase of a Fissure Eruption," *Amer. Jour. Sci.*, Vol. XIV (5th ser.; 1927), pp. 228–30.

[5] G. E. Goodspeed, "Geology of the Gold Quartz Veins of Cornucopia, Tech. Pub. 1035," *Mining Technology*, Vol. III (Amer. Inst. Min. Met. Eng., 1939), pp. 1–18.

[6] A. C. Waters, "Concerning the Differentiation of Lamprophyric Magma at Corbaley Canyon, Washington," *Jour. Geol.*, Vol. XXXV (1927), pp. 158–71.

show a rude columnar structure of quartz and feldspar with a few slender crystals of hornblende oriented at right angles to the dike walls. Such structures, coupled with a tendency toward idiomorphism and the contemporaneous association of low-temperature minerals such as carbonates, chlorites, and zeolites, suggest that these dikes and veins were filled with a more tenuous and perhaps an

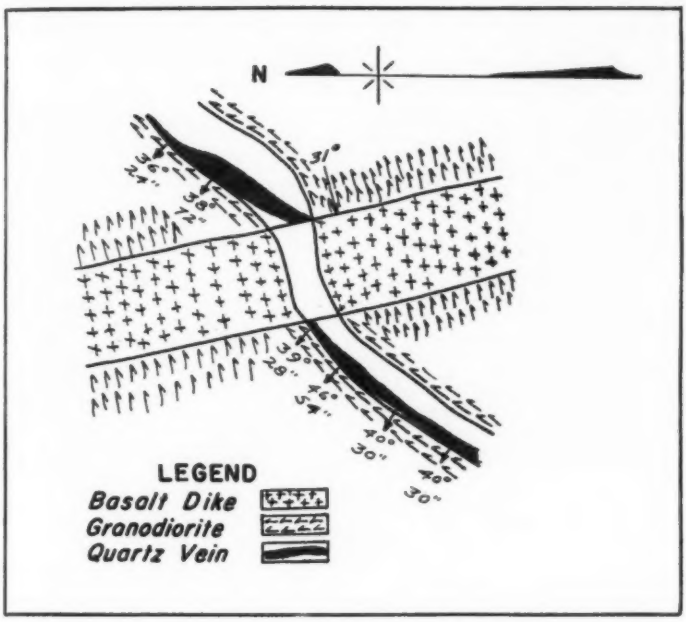


FIG. 1.—Offset in a gold-quartz vein caused by the dilation of a 25-foot basalt dike, on the Union Companion Vein, 2,000-foot level, Cornucopia, Oregon.

aqueous solution rather than a magma of hot silicate melt. This interpretation is strengthened by the fact that some of the feldspar crystals actually extend beyond the contact of the dike, and where they penetrate the wall rock they surround and include the finer mineral constituents of the schistose hornfels, producing sieve or helizitic structures. In this respect they exhibit to a minor degree some of the characteristics of replacement dikes.

REPLACEMENT DIKES

Although all the basalt and diabase dikes and some of the pegmatitic and aplitic dikes at Cornucopia may be adequately explained by the mechanism of dilation, many of the aplite and porphyry dikes in this vicinity fail to produce any offset where an earlier dike or vein is intersected at an angle. This failure to offset may be explained by lateral movement along the walls of the fissure of such direction and amount as exactly to annul the offset produced by widening of the fissure as the dike filled it. Such a coincidence might suffice for one

FIG. 2.—An aplite dike intersecting an earlier porphyry dike at an angle without offset.

occurrence but is not sufficient to explain many occurrences. It is, however, perhaps not surprising that relatively few cases of lack of offset have been described in the literature, for, even where this feature may be readily observed in the field, it is not always appreciated in a cursory examination (Fig. 2).

Lack of offset was noted by Billings in his study of the large diabase dike at Medford, Massachusetts, and explained by a stoping rather than a dilation mechanism.[7] For a dike as large as the Medford diabase this explanation may well be adequate, since the material to be removed might sink or rise as a single block or as many

[7] Marland P. Billings, "On the Mechanics of Dike Intrusion," *Jour. Geol.*, Vol. XXXIII (1925), pp. 140–50.

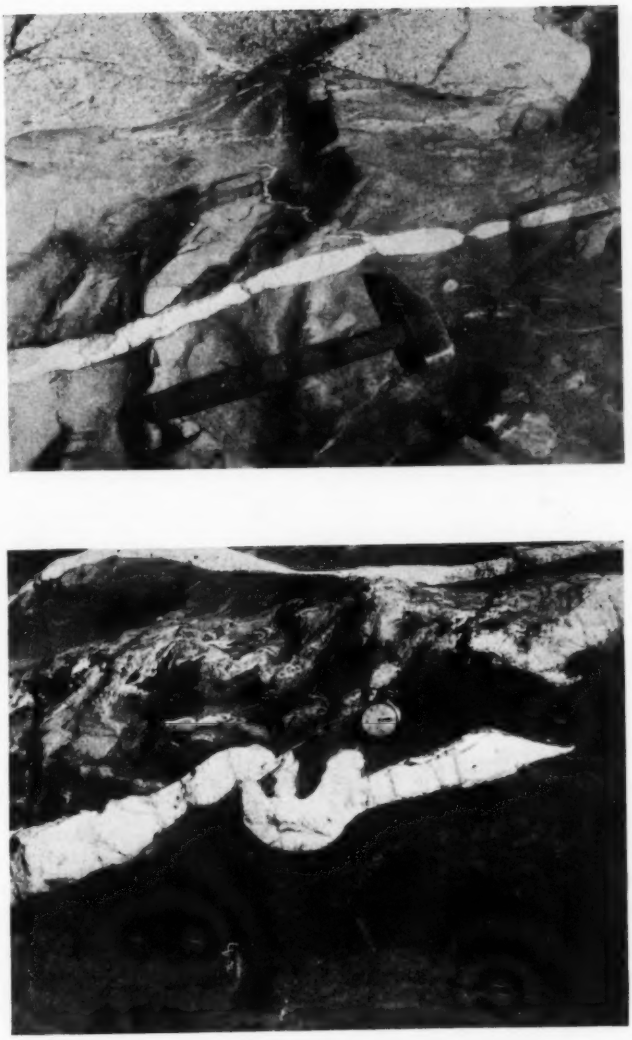


FIG. 3.—Small aplitic dikes showing extreme variations in width

fragments. In small dikes, especially those that are irregular in shape and width, the functioning of such a process would be improbable.

At Cornucopia, Oregon, many small aplitic dikes exhibit extreme variation in size and width. They pinch and swell in such an irregular manner that explanation by dilation would be incongruous even with the added assumption of lateral movement (Fig. 3). These dikes bear a marked resemblance to replacement veinlets of the quartz-garnet-epidote type which range from a fraction of an inch to

Fig. 4.—Contact of porphyry dike with hornfels showing apophyses gradational into hornfels.

over 2 inches in width and are commonly lenticular in habit.[8] The central portion of these veinlets is commonly rather coarse-grained garnet and quartz, with occasional idiomorphic grains of pyrite, while the borders are fine-grained diopside and epidote. Although the contrast in color and texture between the mineral of the veinlet and the dark-gray schistose hornfels of the wall rock as a rule superficially suggests a sharp contact, closer examination indicates a gradational relationship. Even within the veinlets a banding parallel to the schistosity of the wall rock is often apparent, strongly sug-

[8] G. E. Goodspeed and Howard A. Coombs, "Quartz-Diopside-Garnet Veinlets," *Amer. Min.*, Vol. XVII (1932), pp. 554–60.

gesting an inherited structure. The field evidence in respect to these features is fully corroborated by studies of numerous thin sections.

The similarity in form between some of the aplitic veinlike dikes and the quartz-garnet veinlets suggests a similarity of origin, and this suggestion is strengthened by the fact that a number of small veinlike dikes at Cornucopia are intermediate in mineral composi-

FIG. 5.—Aplitic dike with thin septa of hornfels across the dike

tion between normal aplites and quartz-garnet-epidote veinlets. At a locality near Red Mountain, in this region, a small granitic dike or veinlet apparently merges with a quartz-garnet-diopside veinlet in such a way as to suggest that both were formed at nearly the same time. Many of the porphyries contain garnet, epidote, and allanite, which have apparently been formed either earlier or contemporaneously with the plagioclase. It might be difficult to explain the formation of some of these minerals from a normal magma.

Careful examination of the contacts of some porphyry dikes by means of large-sized polished sections discloses irregular apophyses extending into the wall rock. The peculiar feature of some of these projections is that their apices converge into very thin quartz-feldspar veinlets, punctuated at intervals with larger crystals of feldspar which also occur beyond these apophyses as scattered porphyroblasts in the schistose hornfels (Fig. 4). Small apophyses which in the field appear to be identical in mineral composition with

FIG. 6.—Leucocratic dike showing alignment of mafics

the parent-dike are seen in thin section to contain a very considerable portion of the wall-rock material in their groundmass with local undisturbed relics of fine alignment of the schistose wall rock. Some apophyses show extreme variations in mineral composition, ranging from the "normal" constituents of a porphyry or aplite at the junction with the main dike to nearly pure quartz at their veinlike termination in the wall rock.

In some granitic dikes at Cornucopia thin wedge-shaped sliver-like projections of the wall rock extend into the dike, and in some small aplitic dikes thin septa of the hornfels extend across the dike

from wall to wall (Fig. 5). In one dike about 2 feet in width there are narrow platy extensions of the schist wall 8–10 inches in length. Such features in dikes may be explained more easily as relics which have resisted replacement processes than by the usual interpretation of dilation and magmatic injection.

Unattached inclusions might occur in either dilation or replacement dikes. However, inclusions of schistose rock showing perfect alignment with the schistosity of the wall rock, or inclusions with delicate lacelike outlines which might easily have been disturbed by

FIG. 7.—Contact of a porphyry dike and hornfels

magmatic flow, indicate a more complicated mechanism than that of simple injection. In some thin sections detached relics or crystals of the wall rock survive in the dike with optical continuity indicating absence of the slightest movement (Fig. 6).

Plagioclase porphyroblasts in hornfels adjacent to many replacement dikes exhibit characteristic sieve and helizitic structures, and individual crystals may be seen in the various stages of development from incipient xenoblasts to idioblasts.[9] Recrystallization borders are common, and in some dikes there is a recognizable gradation from the wall rock (schistose hornfels) to the dike rock (quartz

[9] Goodspeed, "Development of Plagioclase Porphyroblasts," *Amer. Min.*, Vol. XXII (1937), pp. 1133–38.

diorite porphyry) (Figs. 7 and 8). Some dikes display coarsely crystalline borders, whereas others are even-grained throughout. Some granitic and aplitic dikes show a concentration of mafic constituents either along the border within the dike or else in the wall rock immediately adjacent to the dike (Fig. 9).

In many of the so-called porphyry dikes the finer-grained groundmass is practically identical with the country rock in texture and composition, and, even though most of the larger crystals in the dike are well formed, their borders commonly show a molding around the

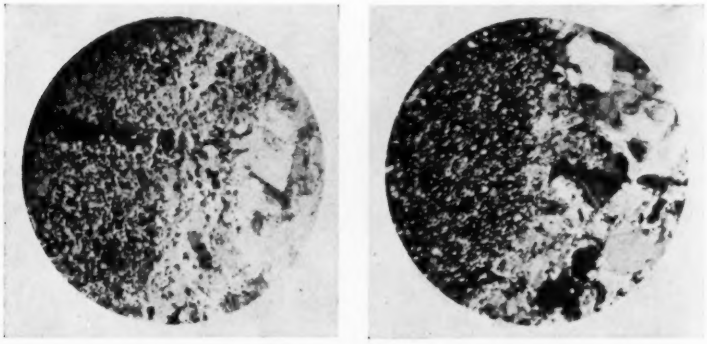


FIG. 8.—Photomicrographs of contacts of replacement dikes with hornfels. Note the feldspathization extending into the hornfels.

finer constituents which is strongly suggestive of a porphyroblastic origin. Minerals included in these crystals are similar to the minerals in the groundmass and the wall rock and do not form a harmonious magmatic assemblage. For example, calcic plagioclase is associated with quartz.

Although, superficially, replacement dikes resemble dilation dikes, it is noteworthy that at Cornucopia they do not maintain the regularity in trend and width of some of the basalt and diabase dikes of this vicinity. One prominent porphyry dike-cutting hornfels is about 12 feet in width high up on the mountainside, but a few hundred feet lower down this dike divides into several narrow dikes. In this region the replacement dikes are most conspicuous where they

consist of light-colored quartz-diorite porphyries, granophyres, and aplites and where they traverse dark-colored hornfels.

MECHANISM OF REPLACEMENT DIKES

Many field and petrographic facts favor replacement, but this interpretation would remain a speculation were it not for the cogent evidence of transitional stages. At Cornucopia there are many dikes which exhibit all stages of development from mineralized fractures

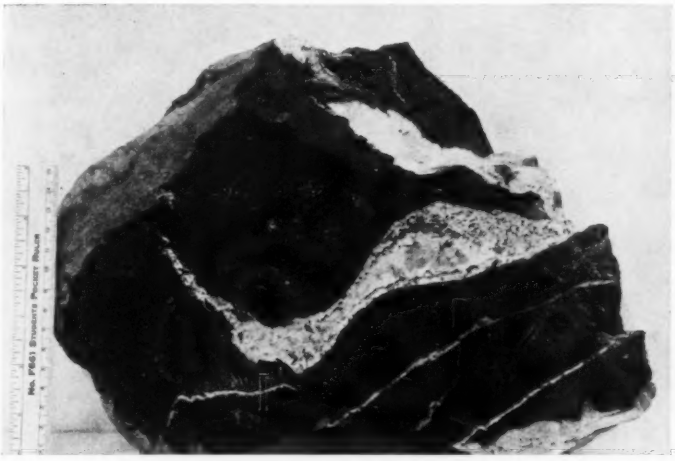


FIG. 9.—Pegmatitic dike with mafic-rich borders

to actual dikes. Where these dikes traverse granodioritic rocks, the initial stage is represented by ill-defined fracture planes, along which the gray plagioclase of the granodiorite has been changed in places to pink feldspar (Figs. 10 and 11). In thin section it is noticeable that the original plagioclases have become turbid and have been replaced in part by orthoclase and sodic plagioclase. This alteration can best be explained by the passage of hydrothermal solutions into either wall. The first stages in the formation of certain gold-quartz veins show similar effects, although in this case the alteration bands are finer grained in texture and have a considerable increase in sericite

and quartz. The formation of feldspar instead of sericite may be an indication of a slightly higher temperature, although there is no theoretical necessity for extremely high temperatures.

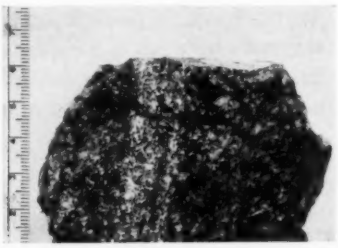


FIG. 10.—Initial alteration bands in granodiorite

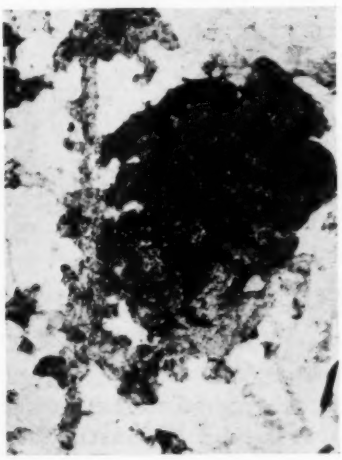


FIG. 11.—Photomicrograph of an alteration band. The altered feldspar near the center of the field is about 2 mm. long.

Where these dikes cut the hornfels their mechanism is apparently similar to that just described for those intersecting granitic rocks, but in the early stages the results are much more varied. Hornblendic, diopsidic veinlets, and veinlets with varying amounts of

FIG. 12.—Feldspathized bands interspersed with long thin relics of hornfels. Note porphyroblasts in the adjacent hornfels.

carbonate, epidote, and chlorite are as common as the quartzose feldspathic veinlets. Some small dikes traversing hornfels are very irregular in shape and are analogous to quartz-garnet-diopside veinlets.

If the fracture planes are far apart and if no recurrent fracturing has taken place, only streaks of alteration are the final result. Not-

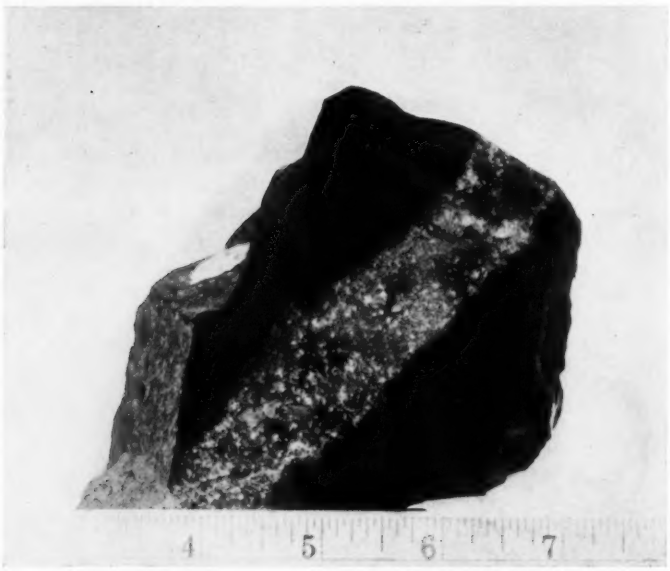


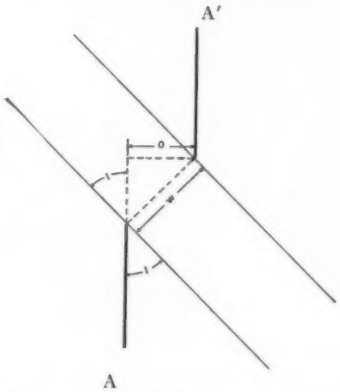
FIG. 13.—Replacement dike in an early stage of development. Note abundance of hornfelsic material in the dike and initial feldspathization along borders.

withstanding these limiting conditions, some alteration veinlets exhibit at intervals a marked lenticular enlargement, although the veinlet itself may not be over 1 mm. in width. Such streaks of alteration or replacement veinlets are of common occurrence in other areas of metamorphic and plutonic rocks in the Pacific Northwest.

The next stage in the development of replacement dikes is characterized by alteration proceeding outwardly from several closely spaced fracture planes leaving but thin septa of unaltered rock (Fig. 12). This stage is easily recognized if there is a contrast in color, such

as dark hornfels against light-colored feldspar and quartz. Since it is a transition stage, even such conspicuous features are readily obliterated by further recrystallization replacement (Fig. 13).

At a later stage the parallel bands of crystalloblastic development merge with one another so that all the material which is in the zone of maximum permeability between the two outermost fracture planes becomes an interlocking mass of crystals formed by metasomatic replacement. Relics of the dividing septa appear as long thin inclusions parallel to the walls of the dike. However, these in-



A and *A′* = Distinctive feature of wall rocks
W = Width of dike
O = Amount of offset
I = Angle of intersection
O = W sin (90–I)

FIG. 14.—Dilation dike. Magma admitted by simple widening of fissure without lateral movement of walls.

clusions inherit their original structural features which may be oriented at an angle to the trend of the dike.

In the final stage all vestiges of original material between the defining surfaces are replaced, and the solid mass of new material between the two outermost fracture planes has the appearance of an injected dilation dike.

It is obvious that closely spaced fracture planes intersecting an earlier structural unit at an angle will cause no offset of this member, provided there has been no movement along the fracture planes. If there has been movement along the fracture planes, offset will take place, but the amount of offset need not be proportional to the width of the zone of fractures. One of the best criteria for distinguishing

dilation from replacement dikes is the structural evidence of offset or displacement of any distinctive feature such as an earlier dike, vein, band, or layer in the wall rock. If the movement is that of a simple widening of a fissure, and entirely in a direction normal to the strike of the dike, the amount of displacement will be equal in amount to the width of the dike multiplied by the sine of the angle complemen-

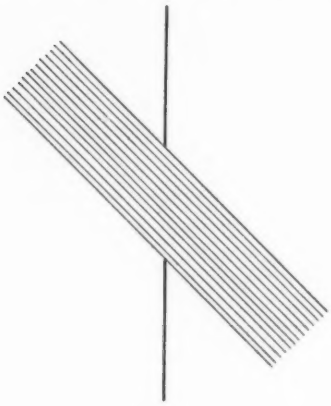


FIG. 15

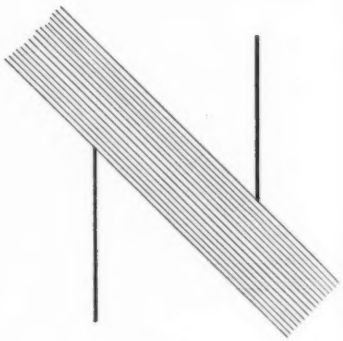


FIG. 16

FIG. 15.—Replacement dike. No movement along individual fracture planes; therefore no offset of earlier structural features. Minerals such as feldspars and quartz are formed as the result of solutions penetrating the closely spaced fracture planes. As the thin intervening screens of wall rock are replaced, the body assumes the appearance of a homogeneous dike.

FIG. 16.—Replacement dike. Considerable lateral movement along the closely spaced fissures produces an offset far in excess of that produced by simple widening of a dike fissure.

tary to the angle of intersection of the dike and the earlier feature (Figs. 14, 15, 16, and 17).

Replacement dikes vary considerably mineralogically, depending presumably upon the chemical character of the activating solutions, the nature of the rock that has been replaced, and the reactions which have taken place. At Cornucopia porphyries are more common in hornfels, whereas aplites and pegmatites are common in both hornfels and granitic rock. The formation of a replacement dike may

be considered to be essentially a result of additive metamorphism, yet it must be borne in mind that certain elements have to be removed to make room for those which are introduced. Granitic dikes in a basic hornfels are perhaps due chiefly to the addition of silica and alkalies, and the removal of iron and magnesia is evidenced by basic zones in the wall rock or by mafic borders of the dike.

Although it is probable that in many replacement dikes the fracture planes are parallel to two main planes which form the walls of the dike, yet some dikes show evidence of a series of parallel frac-

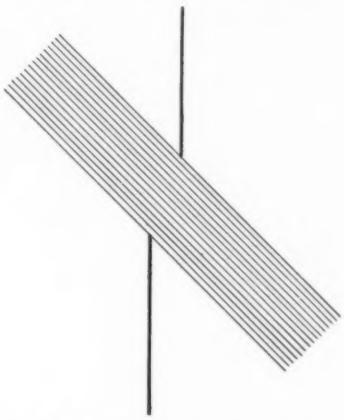


FIG. 17.—Replacement dike. Slight lateral movement along the closely spaced fissures produces less offset than would be obtained by the widening of the fissure.

tures transverse to the walls. Dikes in the formative stage show transverse veinlets separated by altered rock. In fully formed dikes the presence of transverse fractures is suggested by lines of feldspar porphyroblasts diagonal to the trend of the dike. These fractures are presumably analogous to those transverse to main shear planes as noted by many workers in structural geology.

Dikes showing transitional facies are not so common as the fully formed dikes, yet they are not rare. A single dike may exhibit several closely associated stages. One side of a large specimen shows a "normal" aplite dike, while a few inches away on another face feldspathization is confined to two parallel fracture planes, and much of

the material between these fractures is unaltered granodiorite (Fig. 18). It is quite possible that the origin of some aplitic and pegmatitic dikes may be in part dilation and in part replacement. Comb structures, combined with crystallographic extension of the dike minerals into the walls and partially replaced but undisturbed inclusions, sug-

FIG. 18.—Relationship of alteration bands to an aplitic dike

gest tenuous aqueous solutions rather than orthomagmatic silicate melts (Fig. 19).

In a number of recent papers it has been suggested that replacement processes may play an important role in the formation of igneous-appearing rocks.[10] Bastin believes that certain aplites in On-

[10] G. H. Anderson, "Granitization, Albitization, and Related Phenomena in the Northern Inyo Range of California-Nevada," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), pp. 1–47; R. W. van Bemmelen, "On the Origin of the Pacific Magma Types in the Volcanic Inner Arc of the Soenda Mountain System," "De Ingenieur in Neodor-Indie," Ser. IV, *Nederlandsch-Indie Misnbouw en Geol.*, Jaagang IV (1938), pp. 1–15; Helge G. Backlund, "The Problem of the Rapakivi Granites," *Jour. Geol.*, Vol. XLVI

tario are of hydrothermal origin.[11] Perhaps, however, favorable structural features should be emphasized, since in replacement dikes they may not only afford the means for the passage of solutions but would also account for the relatively sharp borders. Structural petrologists have noted the interdependence of these factors in the formation of certain metamorphic rocks. Although the recognition

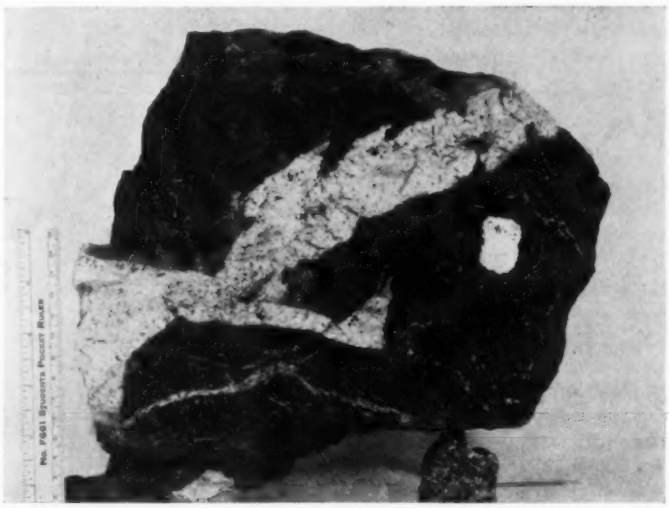


FIG. 19.—Pegmatitic dike showing partial replacement

of a replacement or dilation dike may be of little importance in determinative petrography, it is of much consequence in questions of petrogenesis to be able to distinguish between metamorphic processes and magmatic injection (Table 1).

(1938), pp. 339–97; J. Gilluly, "Replacement Origin of the Albite Granite near Sparta, Oregon," *U.S. Geol. Surv. Prof. Paper 175-C* (1933), pp. 65–81; Goodspeed and Coombs, "Replacement Breccias of the Lower Keechelus," *Amer. Jour. Sci.*, Vol. XXXIV (1937), pp. 12–23; Goodspeed, "Small Granodiorite Blocks Formed by Additive Metamorphism," *Jour. Geol.*, Vol. XLV (1937), pp. 741–64; T. T. Quirke and W. H. Collins, "The Disappearance of the Huronian," *Geol. Surv. Canada Mem. 160* (1930); Doris L. Reynolds, "Demonstrations in Petrogenesis from Kiloran Bay, Colsonay. I. The Transfusion of Quartzite," *Min. Mag.*, Vol. XXIV (1936), pp. 367–407.

[11] E. S. Bastin, "Aplites of Hydrothermal Origin Associated with Cobalt-Silver Ores," *Econ. Geol.*, Vol. XXX (1935), pp. 715–34.

A dilation dike records one of the chapters in the magmatic history of an injected melt, even though it may be just a sample of a larger changing mass of magma. The certainty of the mechanism of injection should be established before using the composition of dikes to suggest large-scale differentiation in a hypothetical magma chamber. In contrast to orthomagmatic dilation dikes, those formed by replacement may represent merely an episode of either progressive or retrogressive metamorphism. Instead of the simple cooling of an injected melt, the thermal conditions may have been more complex, involving both rising and falling temperature. In general, the variable factors involved in the formation of replacement dikes are: (1) the nature of the original material, which may have presented a wide range of mineralogical, textural, and chemical differences; (2)

TABLE 1

COMPARISON OF FIELD AND PETROGRAPHIC FEATURES OF DIKES

DILATION DIKES	REPLACEMENT DIKES
Field	Field
1. Offsets of wall rock units usually proportional to width of dike and angle of intersection	1. Units in wall rock may be extrapolated across dike without offset or with disproportionate offset
2. Uniform widths characteristic; irregularities usually local	2. Extreme variations in width with pinching and swelling
3. Inclusions, if present, may show the effect of magmatic flow and optalic metamorphism	3. Inclusions not disturbed by magmatic flow; inclusions may show effects of recrystallization
4. Columnar structure at right angles to the cooling surfaces may be present	4. Relics of wall-rock structure may be traced across dike; small dikes may have bridgelike septa of wall rock
5. Composition may be uniform for great distances	5. Composition and texture may change within short distances
6. Apophyses retain the composition of the parent-dike	6. Apophyses may differ in composition from the main dike
7. Chilled borders common	7. Coarse textures along borders common
8. Sharp borders characteristic	8. Gradational as well as sharp borders
9. Transition zones or transitional terminations rare	9. Reaction zones may be present; some dikes show transitions to veins

TABLE 1—*Continued*

Petrographic	Petrographic
1. Glassy borders may be present	1. No glassy borders or chilled borders
2. Progressive increase of grain size toward center of dike	2. Texture may be uniform throughout dike or may show wide variations
3. Typical igneous textures such as intersertal, intergranular, etc.	3. Granulitic and crystalloblastic textures common
4. Phenocrysts show typical pyrogenetic features; clear crystals common; glass inclusions in plagioclase affected by crystal growth showing rectangular outlines bounded by crystallographic planes	4. Phenocrysts may have features indicating porphyroblastic origin; turbidity due to included material and complex twinning common; included minerals in plagioclase may not belong to a magmatic sequence
5. Inclusions may exhibit definite magmatic reaction zones, e.g., development of pyroxene around grains of quartz	5. Inclusions in all stages of recrystallization may be locally abundant, and delicate relics may be undisturbed
6. High-temperature minerals abundant, with low-temperature minerals limited to deuteric alteration	6. Contemporaneous low-temperature minerals of primary origin usually conspicuous
7. Usually a clear demarcation between the minerals of the material of the dike and the wall rock; glassy mesostasis may be present.	7. Wall-rock material may extend into dike and be interstitial with respect to the crystals of the dike; crystalloblastic extension of dike minerals into wall rock

the nature of the active solutions or emanations including their initial physical chemical conditions and the changes produced by their reaction with the original material; and (3) the nature of the effects of stress which permit the passage of solutions and emanations. These stresses may have produced recurrent fracturing which was, perhaps, influenced by the structural condition of the original material or by the product of the concomitant replacement. The development of new crystal aggregates may thus have completely obliterated earlier stages of the process of their formation. Hence, what finally appears as a simple body may, in reality, be the result of a complex process, of which it shows clear evidence of only the final stage.

CHERT IN THE GRENVILLE MARBLE, ROSS TOWNSHIP, RENFREW COUNTY, ONTARIO

W. A. TARR AND W. D. KELLER
University of Missouri

ABSTRACT

Chert in the pre-Cambrian Grenville marble was discovered by the senior author in Ontario and in New York. Its occurrence in the pre-Cambrian rocks resembles that in younger rocks so closely that a similar origin is postulated. Evidence is given to support a primary origin, i.e., primary chert in the original Grenville limestone before metamorphism. A thin-section study of the minerals developed at the contact of the chert and the carbonates is included. The paper was begun by the senior author but has been finished posthumously by his wife and the junior author.

INTRODUCTION

Field and laboratory work on this problem was begun by Professor Tarr before he was attacked by illness which continued until his death. During the time he was bedfast he referred to his notes and wrote this manuscript beginning with the second paragraph of the introduction and continuing through the field description of the chert. Although he intended to write in detail, later, his conclusions that the pre-Cambrian chert was primary, and to present the evidence therefor, the opportunity was denied him. The junior author, having discussed the problem with Professor Tarr, is stating his (Tarr's) conclusions as revealed in their conversation and from Dr. Tarr's notes. Quotation marks enclose the portions taken verbatim from the field notes. Mrs. Tarr, always a co-worker with Professor Tarr in his research, has lent the notes and read the manuscript.

This paper describes an occurrence of chert in the Grenville marble (limestone) discovered by the senior author June 8, 1934, while making a detour, made necessary by the construction of the highway between Pembroke and Renfrew, in Renfrew County, Ontario. The detour began at Cobden, the road turning to the left (northeast) and returning to the highway at Haley, about 10 miles northwest of Renfrew. The exposure of the Grenville marble and its enclosed chert is about 5 miles northeast of Haley. In order to

secure additional information and collect more specimens, Tarr visited the locality again on September 9, 1935. Tarr wrote the account of the occurrence, and the interpretation of the origin and the other deductions regarding pre-Cambrian chert are his. He asked his colleague, Professor W. D. Keller, to make a petrographic study of the samples of chert and associated minerals occurring in the marble, and his report is incorporated in the paper. It contributes some interesting information on the mineralogical changes induced by the metamorphism to which the original limestone and chert have been subjected since they were deposited in pre-Cambrian times.

GEOLOGY OF THE AREA

The geology of the area is shown on Pembroke Sheet 122, in *Report 977*. Ells[1] shows the Grenville marble covering a number of square miles in Ross township and adjacent areas. A few miles to the west, gneisses and related rocks occur and continue far in that direction. There is a small area of anorthosite within a mile of the locality in which the chert is found in the Grenville marble. The anorthosite is believed by Ells to be intrusive into the marble.

LOCATION

The marble dips 45° slightly north of east. On Sheet 122 the 45° dip and strike symbol, about 1 mile west of the anorthosite, is probably the location of the outcrop of the marble showing included chert that I first discovered. This is referred to as Locality 1. About $\frac{1}{2}$ mile southeast is a second outcrop of the marble (Locality 2). It is an elongated exposure from 200 to 400 feet wide. Gneisses and schists occur in the marble to the southeast of this exposure. Both of these marble outcrops stand out as low, elongated hills. The marble from Locality 2 extends south across the road, and, as it is free from the chert or other siliceous material, a marble quarry has been opened in it, though not much marble has been removed. Continuing along the road to the first corner and then turning southwest, marble was found exposed along the road for about 0.7 mile. At a distance of 1.3 miles from the corner a very cherty marble

[1] R. W. Ells, "Geology and Natural Resources of Northwest Quarter-Sheet 122, of the Ontario and Quebec Series and Comprising Portions of the Counties of Pontiac, Carleton, and Renfrew," *Geol. Surv. Canada Rept. 977* (1907).

(Fig. 1) is exposed on the south side of the road. This is Locality 3, and from its position and strike it may be connected with Locality 1. However, the deformation of the marble throughout the area is so intensive that any attempt at correlation would be useless. These three outcrops are the only ones of any importance that were found in the limited time available for the study. A small exposure showing chert was seen along the road about 4 miles from Haley. It was

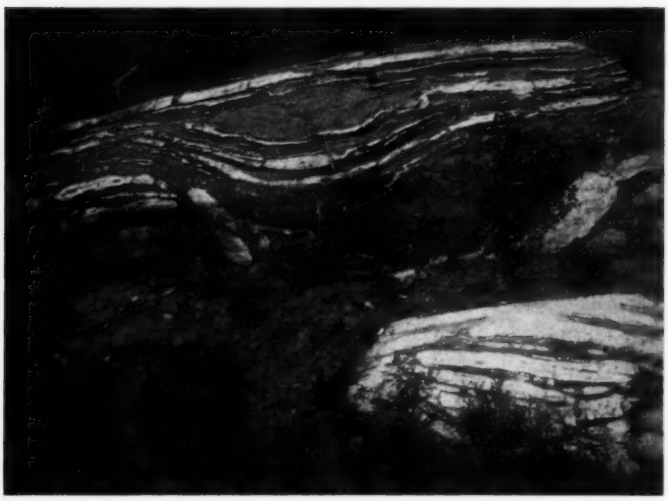


FIG. 1.—Shows banding of bedded chert in coarse-grained Grenville marble. Locality 3.

chiefly of interest because it was less than 100 feet from the anorthosite and because a great deal of diopside had developed in the marble.

THE GRENVILLE MARBLE

The exposures of the Grenville marble were too limited to permit determination of structural details. What appeared to be original banding or bedding was noted in a few places, but these evidences were too poor to be of any value in getting at the structure. Both crumpling and shearing have affected the marble and both would, of course, be factors in any deductions made about the structure

that were based upon the banding noted above. The most significant feature showing the structure of the marble is the presence of the chert, as will be shown later.

The marble is dominantly coarse-grained, the grains being $\frac{1}{4}$–$\frac{3}{8}$ inch across, but some portions are fine-grained, $\frac{1}{16}$ inch across. The color is white or light shades of gray, with an occasional dark-gray area. The marble weathers much faster than the chert, quartz, or silicates. Measurements made in many places showed that the surface of the marble is, on the average, 3 inches lower than the surface of the nodules or beds of chert. Much of the chert still retains the glacial striae. Where the marble had been stripped recently (as at the small quarry), it retains the scratched and polished glaciated surface.

THE CHERT

The term "chert" has been applied to the nodules, lenses, and beds or bands of siliceous material occurring in the marble, because of its striking resemblance to typical chert as it may be seen in limestones in all parts of the world. It was the similarity of this siliceous material to chert that caught my eye as we drove through the shallow cut in the top of the low hill formed by the outcrop of the marble. Having studied the occurrence of chert in numerous places in the United States and Europe, the striking similarity of this material in the pre-Cambrian to the chert seen in the Paleozoic and younger formations aroused my interest at once.

The chert occurs as rounded or irregular nodules, less than an inch to several inches in diameter; as lenses, attaining a length of 5 or 6 feet, and normally a few inches, though occasionally 2 feet, in thickness; and as beds, as thick as 6 inches and of unknown length because of the deformation the marble has undergone. The lenses and beds may be a few inches or several feet apart. In several exposures (Fig. 2) the quantity of chert was greater than in most portions of the very cherty Burlington (Mississippian) limestone in central Missouri. Many of the chert occurrences show evidence of deformation, some lenses being broken and pulled apart and others distorted; yet, as the photographs show, all retain enough of their original features and their relationship to one another to show un-

mistakable characteristics of much younger occurrences of chert. Furthermore, the sharp contact of the chert with the marble (in spite of the development of various calcium silicates) has been retained. Where no silicates have formed, the contact is as sharp as in more recent chert.

(At this point Professor Tarr indicated that the manuscript would continue with specimen, textural, and petrographic descriptions, and

FIG. 2.—Shows abundant chert similar in occurrence to that in younger cherty limestones.

finally with interpretation and conclusions of origin. The junior author continues.)

In general, the chert is white to light gray, but "one specimen found at Locality 2 is so fine-grained and dark (almost a dark gray) as to have the appearance of flint. The dark-colored specimen was a part of a larger nodule that was coarser in grain. Where both chert and marble are fresh, the chert is the lighter [whiter] in color."[2]

The notes imply that fine-grained to dense chert is the rule, but less commonly "this chert . . . . is an integral part of a more coarsely

[2] Professor Tarr's notes in quotation.

crystalline chert." Coarseness of grain was developed through metamorphism of "this chert which was an original product in the *limestone* (now marble)" and which [chert] has "now undergone more or less recrystallization."

The localities studied were close to outcrops of anorthosite, which Ells believed to be intrusive into the marble, or (at Locality 3) to gneiss, which Tarr considered as possibly having been a granite intrusion into the marble on account of the abundant diopside present. He says: "It is possible that the marked development of the pyroxene was due to the proximity of the gneiss (originally granite) as the pyroxene is not so markedly developed in Localities 1 and 2." The development of the Ca and Mg silicates, which Professor Tarr recognized in the field, interested him so deeply that he collected representative hand specimens at various carbonate-silicate contacts for thin-section study. Several of them are described in the following section.

PETROGRAPHY

TYPICAL GRENVILLE MARBLE

This is a very coarse-grained, clean white dolomite showing abundant pressure twinning. A few fine to coarse quartz grains are scattered through the marble. At the contact of one coarse quartz grain with the carbonate, a little diopside has formed in small irregular grains within the original quartz boundary. A small amount of serpentine has formed in narrow veinlets between several of the carbonate grains. Several of these show varying amounts of a brownish iron-oxide stain.

Specimen C-54.—Chert nodule in Grenville marble, due north of Haley, Ontario. The thin section contains dolomite, serpentine, tremolite, and a very fine-grained mixture of minerals having both low and high birefringence, which are probably microcrystalline quartz (chert), carbonate, and tremolite. Positive identification cannot be made because of their fineness and intimate mixing. The carbonates can be recognized definitely, and tremolite is suggested by elongate aggregates having a small extinction angle, high birefringence, and moderate relief. Part of the low-birefringent material has the texture of chert, and some appears slightly fibrous, like

serpentine. Apparently most of the chert has reacted with dolomite, and replacement by tremolite is well advanced.

Specimen C-50.—Tremolite in Grenville marble, Renfrew, Ontario. This section is cut across the contact of invading tremolite and dolomite which is being replaced (Fig. 1). The marble near the contact is composed of clean (clear) smaller rounded dolomite grains, 0.2–0.5 mm. in cross section, set in much larger clouded and "dusty"

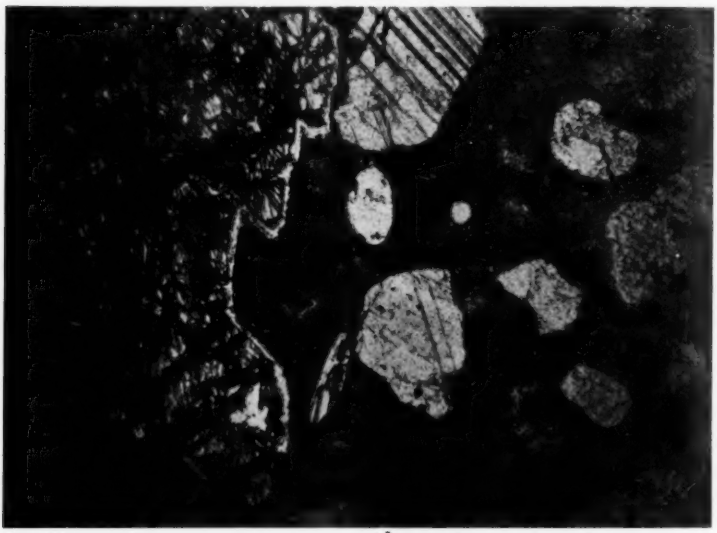


FIG. 3.—Photomicrograph. Tremolite invading dolomite. Crossed nicols. 100×

grains, as in sieve texture. At the immediate contact the edge of the dolomite is marked by a narrow black hairline which may be expanded at a re-entrant cleavage angle of the tremolite. Between this black line and the tremolite is a clear, anisotropic band 0.02–0.5 mm. in width, having an index of refraction close to that of Canada balsam and showing wavy extinction. With no other optical or physical properties determinable, identification of the material in the band is impossible.

The tremolite is advancing into the dolomite along a saw-tooth

edge, the "teeth" being the 55° angles formed by the grain faces of the tremolite.

Presumably the activity incident to the growth of the tremolite is responsible for the clouded dolomite beyond the contact. The black line at the contact probably represents an accumulation of impurities in the dolomite which are rejected by the tremolite and are pushed ahead of it as it advances. The undetermined clear band is probably a transition substance intermediate between host and guest members of the metamorphosing rock.

Specimen C-53.—Diopside crystals smoothed by ice, 5½ miles northeast of Haley, Ontario. The hand specimen appears to be a mixture of fibrous tremolite, dolomite, calcite, and blocky diopside. The thin section shows coarse, interlocking grains of diopside cut by a narrow, irregular, veinlike band of tremolite. At one edge the diopside contacts calcite in which a few slender blades of tremolite are developed.

Specimen C-51.—Chert altered to tremolite and talc, Haley, Ontario. Tremolite needles in random orientation compose one side of a hand specimen and pass very gradually through an irregular contact into fine-grained, light-gray, compact talc. The thin section was cut in a place showing schistose talc carrying many fine short needles of tremolite.

Specimen C-56.—Serpentine after chert in Grenville marble, 6–7 miles northeast of Haley, Ontario. In the hand specimen typical Grenville marble goes to grayish-tan, translucent serpentine through a gradational contact zone about ½ inch in width. In thin section, "islands" of serpentine set in dolomite become more numerous toward the contact zone until finally relics of carbonate remain in serpentine, and then behind this lies the massive serpentine.

Other hand specimens and thin sections were studied, but they do not contribute anything more to the record of the mineral alteration. Since deposition, the chert has reacted with the dolomite to form diopside, tremolite, talc, and serpentine.

INTERPRETATIONS AND CONCLUSIONS

As Professor Tarr had originally planned to write the interpretation of the origin, it seems best merely to state his conclusions and

support them, as far as possible, by quotations verbatim from his notes.

1. Chert was deposited in the Grenville limestone (before metamorphism) as a primary part of that formation. The chert is therefore a primary pre-Cambrian[3] chert. "The parallel arrangement of the chert nodules and lenses is strong proof that this was primary chert." "Finding the chert here [in the recrystallized, bent, deformed, and sheared bands and nodules] also is against the idea of a later movement of silica to *form* chert as is claimed by some." Referring to Locality 3, Professor Tarr says: "This is a fine example, and, I think, strong evidence that chert occurred in the pre-Cambrian! The form, size, relationship to marble, and composition of the material all point, beyond doubt, to a remarkably preserved occurrence of primary chert in Proterozoic or Archeozoic rocks."

From a description of a similar occurrence in the Grenville marble 2–3 miles southwest of Moriah Center, New York, the notes state that, "to me, this means chemical precipitation at the same time the limestone was laid down."

2. Chert was deposited in layers, lenses, and nodules in the pre-Cambrian in the same manner as in the Burlington (Mississippian) limestone of Missouri. The similarity of the field occurrences first directed attention toward field recognition of the chert in the Grenville and is considered strong evidence in favor of a primary origin.

3. The layers and nodules antedate the deformation undergone by the Grenville, for they are bent and sheared. The chert also was recrystallized during metamorphism.

4. Near Moriah Center, New York, far from the Ontario localities, similar chert occurs in the Grenville formation.

5. During metamorphism the chert and dolomite were altered to diopside, tremolite, talc, and serpentine.

[3] Professor Tarr's notes refer to other probable pre-Cambrian flints described by Eliot Blackwelder on page 155 of "Summary of the Pre-Cambrian Rocks of Utah and Wyoming," *Utah Academy of Sciences, Arts and Letters*, Vol. XII (1935). They occur in the Medicine Bow Range of Wyoming where "in some of the massive pure marble beds there are also layers of nodules that were probably flints originally but now have been recrystallized to jasper."

ELLIPTICAL BAYS IN SOUTH CAROLINA AND THE SHAPE OF EDDIES[1]

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ABSTRACT

The elliptical bays (swamps) in Horry County, South Carolina, which the writer has interpreted as lake basins encircled by beach ridges, bars, or atolls, apparently owe their shape and orientation to the tendency of rotary currents in liquids to assume the shape of an ellipse whose longer axis points N. 45° W. in the Northern Hemisphere and N. 45° E. in the Southern Hemisphere. The currents in the lakes were probably induced by breaking waves during a late Glacial epoch.

LOCATION, DISCOVERY, AND MAPS

Among the swamps of Horry County, South Carolina, there is a group of low, elliptical and crescent-shaped sand ridges whose major axes all point N. 45° W. These low ridges, being of lighter color than the swamps beside them, show conspicuously on airplane photographs (Figs. 1 and 2), on which they were first detected about 1932.

At the suggestion of the writer a topographic map of this interesting area has been made by the United States Geological Survey; this map, although not yet engraved, is available as lithographed advance sheets of the Nixonville and Myrtle Beach quadrangles, on a scale of 1/48,000 and with a contour interval of 10 feet.

Before these quadrangles were surveyed the writer supposed[2] that the elliptical bays (swamps) in this region lay on the Pamlico terrace. The new maps, however, show that most of them lie on the Talbot terrace. There are few, if any, on the Pamlico terrace in these quadrangles. A photograph of the area just beyond the north edge of the Nixonville quadrangle shows many on higher land, probably the Wicomico terrace. There seems to be no reason why such features should be restricted to any particular terrace.

HYPOTHESES OF ORIGIN

Melton and Schriever[3] suggested that the elliptical sand ridges and the enclosed swampy bays in this region, as well as similar features

[1] Published by permission of the director of the U.S. Geological Survey.

[2] C. W. Cooke, "Geology of the Coastal Plain of South Carolina," *U.S. Geol. Surv. Bull. 867* (1936), p. 7, Pl. XVII.

[3] F. A. Melton and William Schriever, " 'The Carolina Bays'—Are They Meteorite Scars?" *Jour. Geol.*, Vol. XLI (1933), pp. 52–66.

elsewhere, might be scars made by the impact of a swarm of meteorites. This cause was inferred because of their elliptical shape, parallel orientation, and regularly uneven ridges.

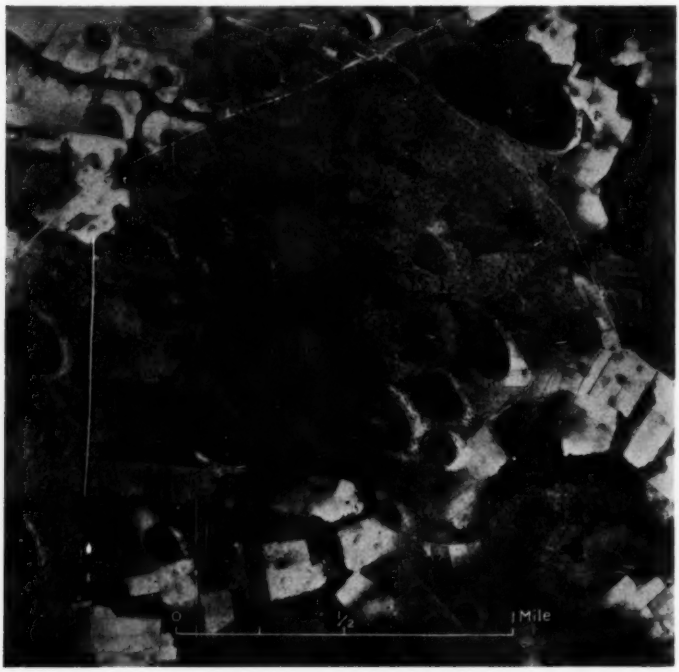

FIG. 1.—Incomplete elliptical rims on swampy lake basins (bays) northeast of Gurley, S.C. Note the curved spit in the double bay near the northeast corner.

The meteoritic hypothesis was challenged by the present writer,[4] who called attention to the smallness of the rims in proportion to the diameters of the enclosed bays, to their orderly arrangement, either contiguous, like beads on a string (Fig. 2), or as groups within larger swamps, and to their location within former waterways. He interpreted some of the rims as beach ridges surrounding extinct-lake

[4] Cooke, quoted in *Science News Letter*, Vol. XXIII (1933), p. 202; "Origin of the So-called Meteorite Scars of South Carolina" (abst.), *Jour. Wash. Acad. Sci.*, Vol. XXIII (1933), pp. 569–70; "Discussion of the Origin of the Supposed Meteorite Scars of South Carolina," *Jour. Geol.*, Vol. XLII (1934), pp. 89–96.

basins and others as sandy atolls built by winds and waves within larger bodies of shallow water. He explained the symmetrical shape as due to the rounding effect of circulating currents on loose sand (note the curved spit in Fig. 1) and doubtfully attributed the parallelism of the axes to a constancy in the direction of the winds.

Douglas Johnson[5] has made the further suggestion that the lake basins may originally have been produced by artesian springs.

FIG. 2.—Segmented lake basins 10 miles north-northeast of Myrtle Beach, S.C.

The writer, however, is still firmly convinced that the bays are extinct lakes and that the rims are beach ridges, bars, and atolls; but he is even more doubtful than at first that their uniform orientation was caused by a preponderance of wind from one direction. If the uniform orientation were merely a local feature, local winds might be adequate to cause it. But similar elliptical bays many miles away show the same orientation. A more general cause must be found.

[5] "Supposed Meteorite Scars in South Carolina" (abst.), *Science*, Vol. LXXIX (new ser.; 1934), p. 461; "Role of Artesian Waters in Forming the Carolina Bays," *Science*, Vol. LXXXVI (new ser.; 1937), pp. 255–58.

FIGURE ASSUMED BY ROTATING CURRENTS

Such a general cause is the tendency of rotary currents in liquids to assume the shape of an ellipse whose major axis points N. 45° W. in the Northern Hemisphere and N. 45° E. in the Southern Hemisphere. As this law is not generally known, the proof is here outlined.

Let us suppose a body of water at rest on the earth. Every particle within it is in equilibrium between two forces—the force of gravity (g) (see Fig. 3), acting toward the center of the earth, and the centrifugal force (c) created by the revolution of the particle

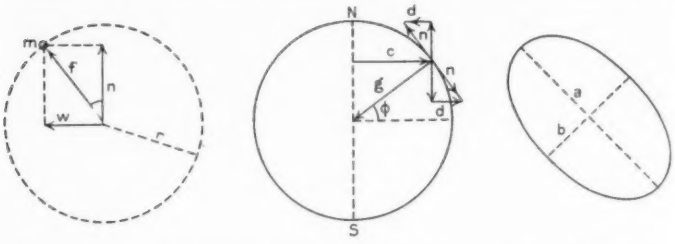

FIG. 3.—*Left*, resolution into north (n) and west (w) components of the centrifugal force produced by a revolving particle; *center*, cross section of the earth, showing resolution of the north and south components (n) into forces acting at right angles (d) and parallel to the axis of the earth; *right*, hypothetical shape of an eddy.

about the axis of the earth (N–S), acting along a line perpendicular to that axis and directed away from it.

Now let us start an eddy or whirlpool within the body of water. The rotation of the water creates centrifugal force (f) acting along every radius of the eddy. The forces along the radii (f) can be resolved into two sets of components, one acting eastward or westward (w), the other acting northward or southward (n), the direction depending upon the quadrant. The east and west components (w) have no effect on the equilibrium of the particles of water because they act at right angles to both of the forces (g and c) that determine its position. The north and south components (n) act nearly at right angles to the force of gravity, but they are inclined to the axis of the earth (N–S) at an angle equal to the observed latitude (ϕ). Therefore they have a subcomponent (d) parallel to the direction of the earth's centrifugal force (c) and opposing it on one side of the equatorial diameter of the eddy and supplementing it on the other.

Every particle of water on the side of the eddy nearer the equator of the earth is pulled upward, away from the axis of the earth, and every particle on the opposite side is pulled downward, toward the axis, the intensity of the pull varying harmonically from zero along the east and west radii to maxima along the north and south radii. Its intensity can be calculated from the equation $d = ms^2 \sin \phi / r$, in which m represents the weight of a unit volume of water at distance r from the center of the eddy at latitude ϕ and moving with a linear velocity s. According to this equation, a metric ton of water moving 20 cm/sec at a distance of 500 meters from the center of rotation at latitude 34° pushes toward or away from the axis of the earth with a maximum force of 4,514 dynes.

The path followed by every particle in the eddy, if unobstructed, would represent a sine curve drawn on a cylinder, i.e., the intersection of a plane tilted at the angle of latitude with respect to the cylindrical boundary of the eddy. But the downward flow of the particle is deflected by the bottom of the pool and the upward flow by its surface. The shape of the eddy, therefore, tends to become that of the projection of a tilted circle, i.e., an ellipse whose major and minor diameters (a, b) bear the proportions $a:b = 1:\cos \phi$. Its shape at latitude 34° N. is somewhat rounder than the ellipse in Figure 3.

Though the maximum and minimum values of d lie due north and south, east and west, respectively, from the center of the eddy, the ellipse is oriented with its axes pointing diagonally between those cardinal directions, because the motion of the water is tangential, not radial. The choice of which axis is to occupy which pair of opposite quadrants is determined by the direction of rotation of the earth, from west to east. Ferrel's law requires that freely moving particles be deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The deflection of the longer, east-west axis is therefore to the northwest-southeast directions in the Northern Hemisphere. In the Southern Hemisphere the axis points N. 45° E. The orientation of the ellipse is completely independent of the direction of rotation of the eddy itself.

The ability to ascertain the shape of an eddy may be of practical importance in hydraulic engineering, for the curvature of the eddy determines the locus of scour and fill. Conversely, the shape of a shoreline may give a clue to the location of the boundaries of such

great eddies in the sea as may have shaped the scalloped coast of the Carolinas.

COMPARISON OF BAYS WITH SHAPE OF EDDY

Melton and Schriever report the mean direction of the major axis of the bays as N. 46° W. The actual direction of several bays, as measured by the writer on photographs oriented by reference to a topographic map, approximates N. 45° W., which is exactly the theoretical orientation.

As the shape and orientation of the bays conform so closely to the figure assumed by an eddy at the same latitude, it seems logical to assume that rotary currents played a part in their formation. That water in the lakes actually contained currents is indicated by the curved spit that partly divides the double bay near the northeast corner of Figure 1.

CAUSE OF THE CURRENT

Apparently the only natural force that will produce currents in small enclosed bodies of water is waves. It may be questioned whether waves of normal duration can give rise to currents of sufficient velocity to record observable effects of the centrifugal forces generated by them. The shape of weak currents will yield to very slight resistance. Moderately strong currents are needed to move sand from their paths and to deposit it in slack water, thus preserving the shape of the current after it has ceased to flow. Strong winds are needed to set such currents in motion. During the glacial epochs such strong winds presumably blew in South Carolina as well as in the Mississippi Valley, where thick accumulations of wind-blown dust attest their power.

CONDITIONS FAVORABLE FOR THE DEVELOPMENT OF ELLIPTICAL LAKES

The conditions required to change an irregular-shaped body of water into an elliptical lake surrounded by a beach ridge appear to be the following: First, there must be wind of sufficient velocity and steadiness to start currents in the lake and to keep them moving for a fairly long time. Second, the margins of the lake must be so shallow that they can rapidly become silted up. In other words, the lake

must be able to assume the figure of equilibrium. Third, there must be at hand a plentiful supply of fine, loose sand or silt to anchor the shores by beach ridges and bars and thus retain the elliptical outline when the wind is not blowing.

Nearly ideal conditions for the formation of elliptical lakes in this hypothetical manner must have existed in Horry County during late Pleistocene time. The sea had recently withdrawn from marine terraces whose slope is commonly less than 1 foot to the mile. The shallow depressions in these plains held pools of water whose very gently sloping edges offered little resistance to the rearrangement of their outlines. The fine, loose sand of which the terraces are built is easily shifted by light waves and gentle currents. When currents moved within a lake, sand filled in the re-entrants of its crooked shore and was heaped up into beach ridges outlining the ideal elliptical shape. Local eddies within the larger lakes were surrounded by sand bars, some of which eventually reached the surface and became atolls. Some long, narrow lakes were divided by bars into elliptical segments as illustrated by Figure 2. Multiple ridges like those shown in Figure 2 can be accounted for by a slight shift of the center of the eddy or whirlpool or possibly by a reduction in the velocity of the current. Intersecting ridges can be explained by a greater shift of center before the original outlines had become firmly impressed.

SUMMARY

The hypothesis that the shape and orientation of the elliptical bays are the result of the natural tendency of all rotary currents to assume an elliptical shape explains all the general characteristics that suggested the meteoritic hypothesis as well as many individual features for which that hypothesis does not account. Forces competent to impose such distinctive outlines would be produced by the rotation of the water body as a unit or as local eddies or whirlpools within it. The immediate cause of such rotation presumably was strong, steady alongshore currents set in motion by breaking waves. The ultimate cause was wind.

PETRIFIED WOOD COMPOSED OF IRON OXIDE[1]

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ABSTRACT

Petrified wood composed essentially of iron oxide occurs in the Wilcox Eocene sand at Shreveport, Louisiana.

Silicified wood of a variety of colors and degrees of porosity is familiar, and petrifactions by pyrite and by calcite are known. Lignitized wood is common, and partly silicified, partly lignitized, pieces have been found. Mine timbers have become impregnated with various minerals, including limonite. But the author has failed to find in the literature mention of truly petrified wood composed of iron oxide. Consultation with several geologists has failed to disclose knowledge of such occurrences.

In the fall of 1935, in Shreveport, Louisiana, local specimens suggesting iron-petrified wood came to the notice of the author. During the half-year following, assisted by students, he collected specimens of unmistakable petrifaction by iron oxide and carefully studied both the material and its occurrence. All specimens examined in place lay in the lower half of thick, irregularly cross-bedded, poorly consolidated Wilcox Eocene sand overlying thin-bedded lignitic clay (also Wilcox) in which are beds or lenses of lignite. The lower portion of the sands is cemented in various degrees by iron oxide while the upper portion contains much lime. Concretionary limestone is abundant above, while below is concretionary iron oxide, often in thin but continuous layers, varying from clay-ironstone and iron-cemented sand to beautifully crystallized botryoidal hematite.

Silicified wood is quite common at various horizons in the Wilcox beds of Shreveport, as also are fragmentary molds of plant detritus in ironstones of various compositions. Occasionally good fossils are found, such as one nearly complete mold of a leaf some 2×4 inches in size.

[1] Based on a paper presented before the Arkansas Academy of Sciences at Conway, April 7, 1939.

Most of the ferruginated wood observed by the author was found in the face of the Red River bluff below Fort Humbug. Each specimen was found encased in a roughly cylindrical crust of sand cemented by iron oxide, hard on the inside but softening rapidly outward. The ends of the crust were open and those of the wood were jagged. The petrified wood itself is hard, compact, and dark brown (resembling hematite) at the core but grades into a brilliant-red, very friable, and very porous material suggesting bark just inside the shell. Both types show wood-grain structure and neither has shown evidence of significant amounts of other material than iron oxide. A few small specimens were found, however, which fitted the foregoing description in all points except color. The softer outer portions were buff while the hard cores were dark, slightly yellowish, brown.

Lack of appreciable residue when the petrified wood is dissolved in HCl disposes of the hypothesis that silica might be the true petrifying agent. Likewise, lack of that residue and of smoking or charring when the material is heated precludes any possibility of simple impregnation. Failure to observe an odor or other evidence of evolution of H_2S (or other gas) on dissolving a specimen in HCl, together with the apparent absence of pyrite from the Wilcox sands of Shreveport, renders improbable an original petrifaction by pyrite followed by oxidation. Thus the material is shown to consist of iron oxide, and that substance is assumed to be the original petrifying agent.

Since announcement of the Shreveport discovery the author has received a specimen[2] showing bits of iron-oxide replacement of wood, which is said to have come from Kansas. Also, he has collected at Winnfield, Louisiana, from presumably Wilcox sand, specimens of petrified wood composed largely of silica but carrying iron oxide in significant quantities.

[2] Contributed by Miss Ruth Armstrong, of Fort Smith, Ark.

DISCUSSION: A NOTE ON PRESSURE STYLOLITES

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University of Chicago

The publication by Shaub[1] of a paper in which he rejects the view that stylolites are developed in solid rock materials, commonly calcareous, as a result of differential solution under moderate pressure (usually due to loading), makes it desirable that those who adhere to this view should present, when possible, additional evidence in its support.

According to Shaub's view, stylolites originated in *unconsolidated* sediments as a result of slow differential plastic flow during compaction under load. The clayey material along the stylolitic partings represents original clayey beds subsequently deformed by the differential plastic flow. Solution processes were not involved.

Impressed or pitted limestone pebbles in conglomerates have been known for many years from several European and Canadian localities, and in some of these occurrences stylolitic partings characterize the places where two pebbles are in contact and contrast strongly with the smoothly rounded peripheries where the pebbles are not in contact. These occurrences and the various hypotheses advanced to account for them have been summarized by Stockdale,[2] who has also pointed out their bearing on the general problem of the origin of stylolites. It seems worth while to describe briefly an excellent example of impressed pebbles from Maryland and to indicate its bearing upon theories of stylolite formation.

A polished slab of "Potomac marble" in the University of Chicago collections came from quarries near Point of Rocks in the Potomac Valley a short distance below Harper's Ferry. The stone is of historic interest because of its use in columns and in other ways in the old House of Representatives chamber, later the Supreme Court room, when the Capitol was repaired after the War of 1812.

[1] B. M. Shaub, "The Origin of Stylolites," *Jour. Sed. Pet.*, Vol. IX (1939), pp. 47–61.

[2] Paris B. Stockdale, "Stylolites: Their Nature and Origin," *Ind. Univ. Studies*, No. 55 (1922), pp. 16–21.

The "Potomac marble" is a conglomerate lentil in the Newark group of Upper Triassic age. A beautiful colored print of it forms Plate XXIII of Volume II of the *Maryland Geological Survey*. Most of the pebbles are dolomite or dolomitic marble, and according to Keith[3] they are very similar to the various types of Shenandoah limestone seen not far away at Frederick, Maryland. They are embedded in a red calcareous matrix, sometimes with a slight admixture of sand. Laterally the conglomerate grades into sandstones and neither has been affected by appreciable metamorphism.

Most of the pebbles are somewhat rounded but a few are angular. Their diameter usually is between 2 and 3 inches.

Figure 1, reproduced from a tracing from a portion of a polished slab, illustrates the significant features, which are: (1) a slight insetting of one limestone or marble pebble in another where such pebbles were in contact and (2) the substitution of stylolitic boundaries for the prevailing smoothly rounded boundaries in such inset-contact portions. It is readily possible to restore in imagination the original evenly rounded outlines in the stretches where they have been destroyed. The stylolites, though incipient and consequently characterized by sinuosities of small amplitude and by the presence of very little argillaceous material along them, are in form identical with the generality of stylolites.

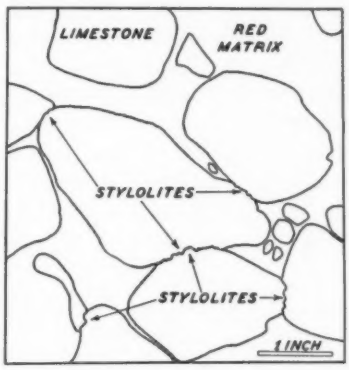

FIG. 1.—Development of stylolitic partings where pebbles of limestone or marble are in contact. Potomac "marble." Tracing from polished surface.

From the described relations it may be concluded:

1. That some of the pebbles were limestone and others marble before they were rounded in the development of the calcareous gravel deposit.

[3] Arthur Keith, "Geology of the Catoctin Belt," *14th Ann. Rept. U.S. Geol. Surv.*, Part II (1894), p. 346.

2. That subsequently mutual solution of the calcareous pebbles took place where two such pebbles were in contact, resulting in a slight insetting of one pebble in another.

3. This peripheral solution of pebbles was not general, for in most places the original smoothly rounded outlines were preserved. Peripheral solution was limited to the places where the pebbles were in contact and it is probable, therefore, that the pressure of one pebble on the other was a factor facilitating solution.

4. The degree of pressure necessary for the development of the stylolites was slight, since there is no evidence either of general distortion of the pebbles or of recrystallization in them since their incorporation in the conglomerate. The pressure was presumably due to loading.

In an article published in this *Journal* in 1933[4] the writer described the relations between cherts and stylolites in southwestern Missouri where stylolites are developed abundantly and to considerable sizes in fairly pure limestones. In this article evidence was presented to show (1) that the cherts had developed by the replacement of limestones, (2) that some of the stylolites had developed *after* the cherts were formed, and (3) that some cherts had been impressed into bordering limestone *pari passu* with the growth of stylolites in the latter.

[4] E. S. Bastin, "Relations of Cherts to Stylolites at Carthage, Missouri," *Jour. Geol.*, Vol. XLI (1933), pp. 371–81.

REVIEWS

Geology and Engineering. By ROBERT F. LEGGET. With a Foreword by P. G. H. BOSWELL. New York: McGraw-Hill Book Co., 1939. Pp. xii+650; illustrated. $4.50.

The increasing importance of geology to certain branches of engineering has resulted in the appearance of several textbooks on engineering geology. Most such textbooks are written by geologists. The present volume departs from this tradition, the author being an engineer with geological training. The result is a refreshing text with a new viewpoint. Instead of the usual treatment on the basis of geological agents, the organization of the book follows subdivisions based on engineering problems.

The first part of the book is devoted to a summary of important geological topics—rocks and minerals, geologic structures, and geological field methods. The second part of the text, which is the main body of the book, discusses the applications of geology to a wide variety of engineering projects. Among the chapters are included such subjects as tunnels, bridge and dam foundations, reservoirs, underground water supply, building foundations, materials of construction, and soil mechanics. At the end of the book is a reference section with a glossary of terms, lists of geological literature sources, and a bibliography of papers referred to in the text.

The treatment of the subjects is logical and clear. As an example of the organization, one may consider the section on bridge foundations. After a discussion of the importance of bridge foundations, the author discusses the preliminary field work, the design of bridge piers and abutments, and special construction requirements. Each of the engineering problems discussed in the section is set within the larger geological pattern, resulting in a well-integrated presentation. Numerous actual examples, with adequate illustrative figures, enhance the interest of the section. The treatment of this sample topic is given about twenty-five pages. All the chapters are well illustrated with line drawings and halftones, and throughout the entire text the author stresses the relation between the geological principles involved and the requirements of practical engineering.

It seems to the reviewer that either of two views may be held regarding the organization of the text. It may be argued that the student using the text receives no detailed presentation of explicit geological principles

organized systematically; on the other hand, one may equally well say that for the engineering student it is more important that the role of geology in engineering be made explicit, and this the text accomplishes very successfully. Instructors in engineering will prefer the present organization; instructors in geology should have little difficulty in weaving in the principles they wish particularly to drive home to the student.

The book deserves the careful consideration of all teachers of geology, who will find within its pages much excellent illustrative material for any course in geology. The point of view of the book is stimulating and it should prove interesting and instructive to students using it.

W. C. KRUMBEIN

A Descriptive Petrography of the Igneous Rocks, Vol. I. By ALBERT JOHANNSEN. 2d ed. Chicago: University of Chicago Press, 1939. xxiv+318; figs. 145. $4.50.

Heavy demand has necessitated the preparation of a second edition of Volume I of Professor Johannsen's work in four volumes, *A Descriptive Petrography of the Igneous Rocks*. This volume has the subtitle *General Petrography*, and the new edition covers the same ground as the first edition. The errata of the earlier edition have, of course, been corrected and some plates have been improved by the substitution of better cuts, but there has been little occasion for revision and the principal differences are in the nature of additions.

More than one hundred pages are given over to the question of classification and the description of the several classifications that have been proposed. Some of these are presented in more concise and usable form than that given by their proposers. To the systems discussed in the earlier edition have been added the classifications of Lacroix and Tröger and that suggested by Hodge has been omitted. The discussion of these systems prepares the way for the presentation of the author's own quantitative, mineralogical, modal classification. In the tabular view of this system it has been possible to fill some of the pigeonholes hitherto unoccupied and, as a result, puglianite, rutterite, gooderite, lakarpite tveitasite, and many others have found their niches. Among old terms malignite now appears in place. Under the suggestive sign of the monkey wrench the author discusses those modifications of his system that have been suggested by others.

The principal addition to the volume is a fifty-one-page Appendix on "Definitions of Rocks" which is a welcome supplement to the other two

appendixes on descriptive terms. The improved edition of the first volume makes the now completed four-volume work the definitive modern descriptive petrography of the igneous rocks.

N. L. BOWEN

Catalogue of Topographic and Geologic Maps of Virginia. By JOSEPH K. ROBERTS and ROBERT O. BLOOMER. Richmond, Va.: Dietz Press, 1939. Pp. xvii+246.

This cartographic catalogue lists the surprisingly large number of 970 items and hence is quite exhaustive. Items are arranged chronologically and grouped into four periods. The work is dedicated to Virginia's pioneer geologist, William Barton Rogers.

The preparation has involved long and painstaking search, which for the senior author has extended over the last twenty years. Judging from a careful examination of the contents, the search must have been thorough, and one can feel that no items of any importance have been omitted.

The title does not do the work justice. It is much more than a mere catalogue since each map listed is followed by a critical comment that gives a very satisfactory idea of the contents and character of the map. The *Catalogue* becomes thus a valuable tool for anyone interested in any kind of study of Virginia for which source data might be expected to be found in map form. Discovery, exploration, settlement, history, economic development, topography, geology, and all other subjects are included.

In addition to the lists of maps with their informative comments there is an interesting chapter devoted to the history of geologic and topographic maps of Virginia. A list of geologic formations now used in Virginia and a table of geological formations as used by William B. Rogers are included.

The work concludes with an index of authors and one of subjects. In the latter the number of citations under a given subject are often surprisingly large. Format, paper, and press work are good.

This publication sets a new standard for future cartographers both by its scope and by its thoroughness.

L. C. GLENN

Geology and Allied Sciences: A Thesaurus, Part I: *German-English.* By WALTHER HUEBNER. New York: Veritas Press, 1939. Pp. 405. $7.50.

This dictionary will fill a need long felt by students of geology. Special attention has been given to local peculiarities in the use of terms in both languages, thus making this thesaurus, with its more than 25,000 entries

in each language, a practically complete collection and co-ordination of German and English terms. The author has not limited the work to strictly geological expressions but, in order to increase its usefulness, has included those from the allied sciences commonly used in geology. However, the omission of commercial and all but the most common mining terminology makes it more useful to the geologist in research than to the geologist in industry.

The volume is well arranged and clearly printed and should be of real value to English-speaking geologists who find it necessary to refer to the German literature. It is planned that Part II, *English-German*, will be published soon as a separate volume.

LOUISE BARTON FREEMAN

"Marine Algae, Coelenterata, Annelida, Echinodermata, Crustacea, and Mollusca," by LEE BOONE. ("Scientific Results of the World Cruises of the Yachts 'Ara' 1928–29, and 'Alva' 1931–32, 'Alva' Mediterranean Cruise 1933, and 'Alva' South American Cruise 1935, William K. Vanderbilt Commanding.") *Bulletin Vanderbilt Marine Museum*, Vol. VII. Huntington, L.I., 1938. Pp. 372; pls. 152.

This volume contains reports on six groups of modern invertebrate marine organisms collected during several cruises under the auspices of the Vanderbilt Marine Museum. In addition to the customary systematic description of the various species, there is presented the geographical and bathymetrical distribution of each. Many of the species are extremely rare, and some are entirely new.

RAYMOND E. JANSSEN

"On the Different Issues of the First Geological Map of England and Wales," by V. A. EYLES and JOAN M. EYLES. *Annals of Science*, III (1938), 190–212; pls. 5–7.

The authors show that although all copies of William Smith's large geological map of England and Wales are dated 1815, there were several issues, the last of which (1817?) was so different from the earlier ones as to constitute what might well be considered a new edition. The authors examined twenty-seven copies of the map. They invite communications from owners of other copies. [Late in 1939 seven more had been brought to their attention.]

A. O. WOODFORD

Geology of North America, Vol. I. Edited by RUDOLF RUEDEMANN and ROBERT BALK. ("Geologie der Erde.") Berlin: Gebrüder Borntraeger Verlagsbuchhandlung, 1939. Pp. 643; pls. 14; figs. 53. Rm. 13.60, unbound; Rm. 16, bound.

This valuable book was begun in 1927 when Professor Erich Krenkel asked Rudolf Ruedemann to write a geology of North America for the comprehensive "Geologie der Erde." Ruedemann asked a number of geologists to collaborate by writing the chapters for their particular fields of research. The editorship was taken over by Robert Balk in 1935. It was found that the subject could not be covered in one volume, so two more volumes are now being prepared by fourteen geologists; the second one will deal with the Cordilleran and Appalachian systems and the Hawaiian Islands; and the third will present the geology of Mexico and Central America.

The contents of Volume I can be best described by giving a list of the chapter headings: "The Physiography of North America," by J Harlen Bretz; "General Geology of North America," "General Paleogeography of North America," and "Climates of the Past in North America," by Rudolf Ruedemann; "The Greater Structural Features of North America: The Geosynclines, Borderlands, and Geanticlines," by Charles Schuchert; "Geology of Greenland," by Curt Teichert; "Geology of the Arctic Archipelago and the Interior Plains of Canada," by E. M. Kindle; "The Canadian Shield," by Morley E. Wilson; "The Appalachian Plateau and Mississippi Valley," by Charles Butts; "Geology of the Southern Central Lowlands and Ouachita Province," by Paul Ruedemann; "The Atlantic and Gulf Coastal Plain, " by L. W. Stephenson, C. W. Cooke, and Julia Gardner; "Canadian Extension of the Interior Basin of the United States," by T. H. Clark, G. M. Kay, E. R. Cumings, A. S. Warthin, Jr., and G. S. Hume; and Index.

Each author has given a remarkably concise account of his own subject and has given good bibliographic references. This book, which is completely and carefully indexed, gives an excellent summary of the geology of North America and should be extremely useful to all publishing and teaching geologists.

LOUISE BARTON FREEMAN

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